

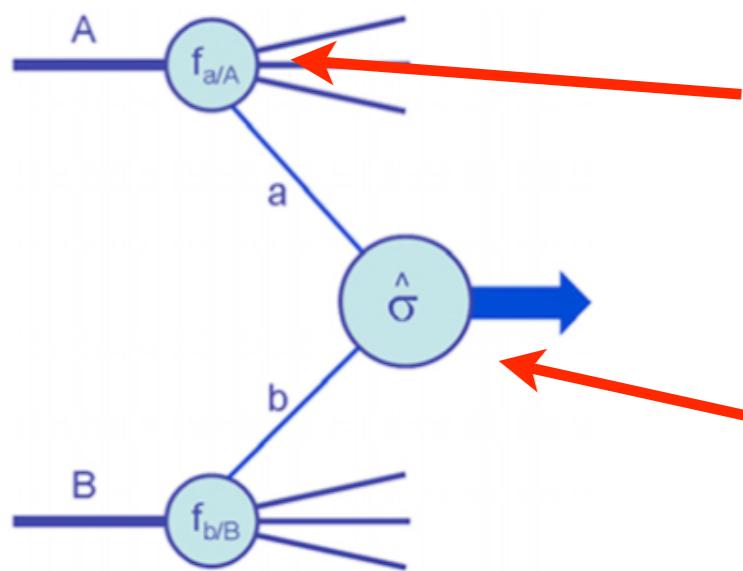
Perturbative QCD: Status

ICHEP 2012, Melbourne, July 10, 2012

John Campbell, Fermilab

Why perturbative QCD?

- ♦ Necessity for a hadron collider



determination of parton distribution functions

calculation of hard scattering matrix elements

Expansion in strong coupling α_s

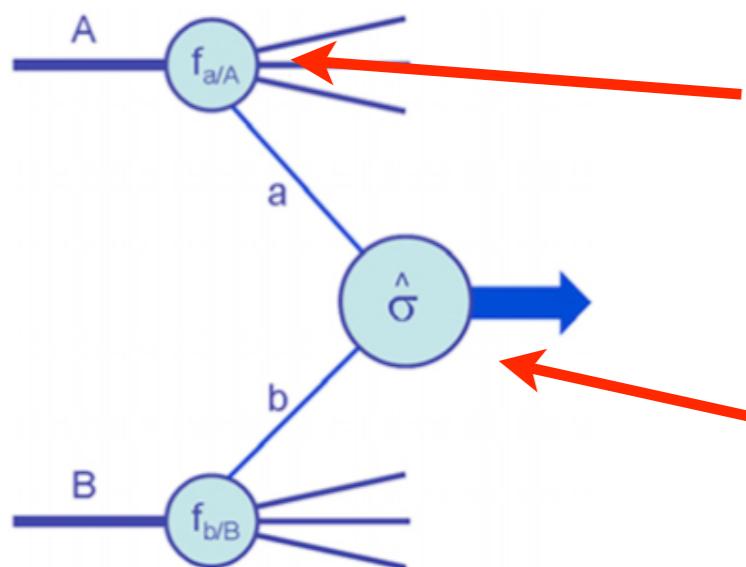
- ♦ Reliable due to value of α_s at relevant scales:

$$\alpha_s(Q) \sim 0.1$$

for $Q = m_W, m_Z, m_t, p_T(\text{jet})$

Why perturbative QCD?

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determination of parton
distribution functions

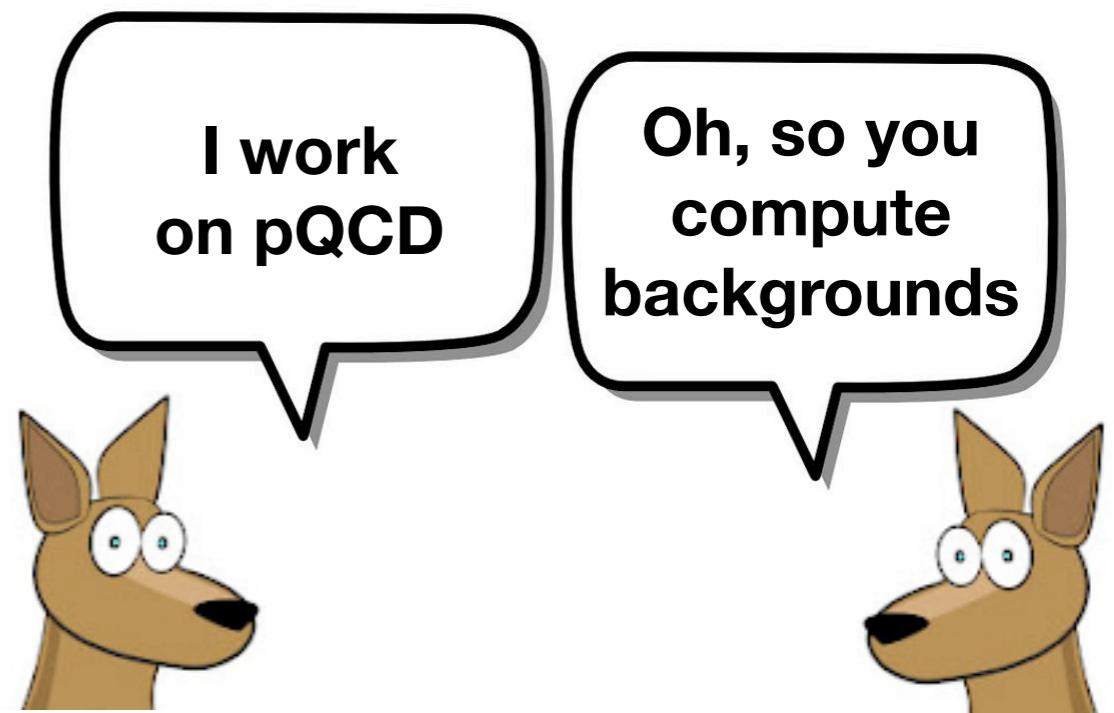
calculation of hard
scattering matrix elements

**Expansion in
strong coupling α_s**

- ♦ Reliable due to value of α_s at relevant scales:

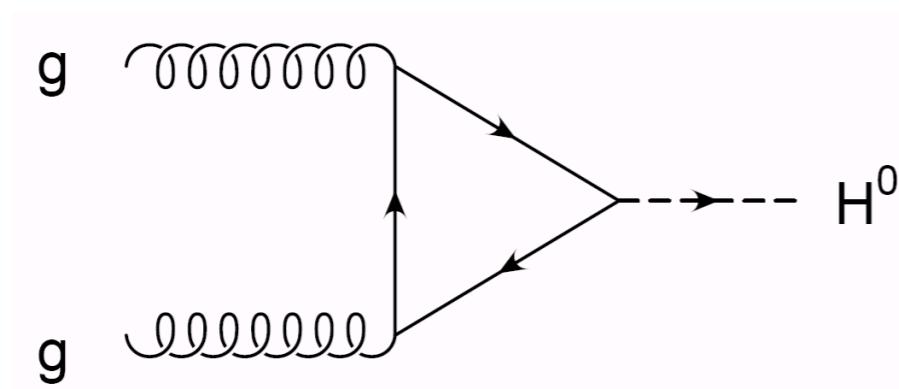
$$\alpha_s(Q) \sim 0.1$$

for $Q = m_W, m_Z, m_t, p_T(\text{jet})$



Higgs and QCD

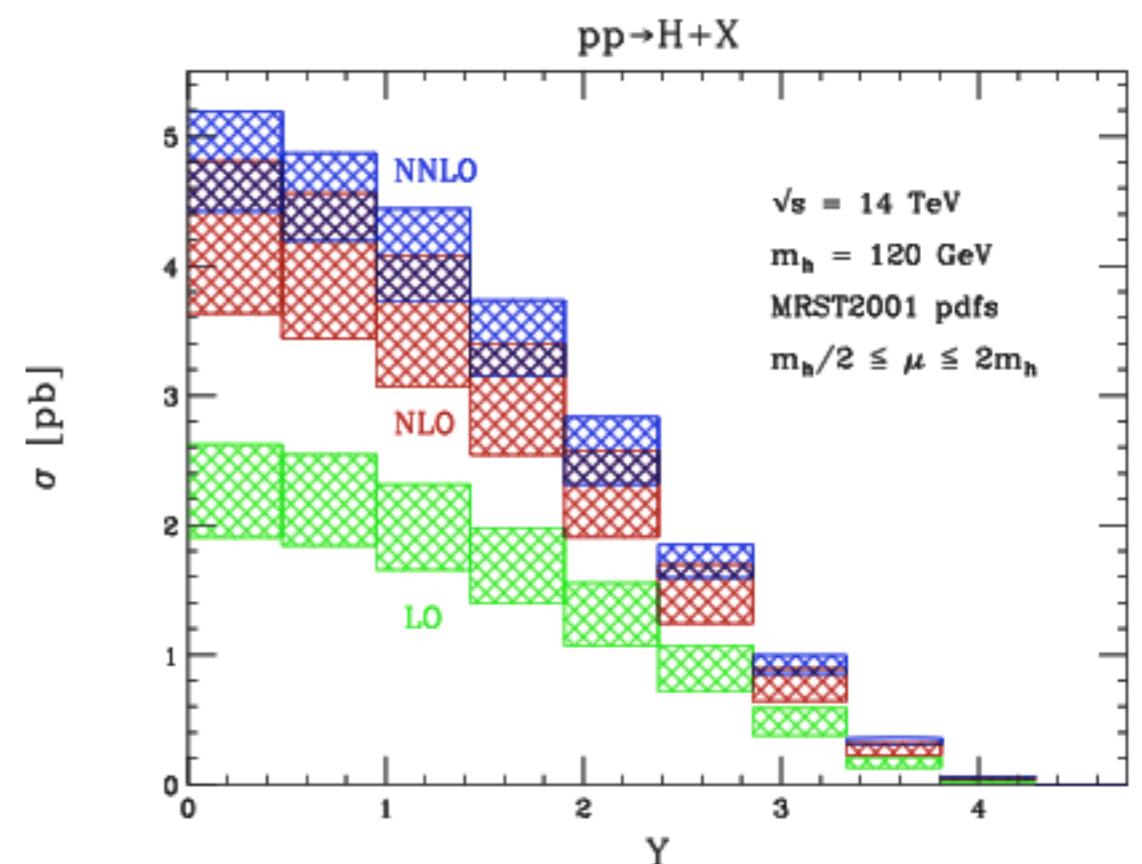
- ♦ Despite EW role a real QCD issue.



- ♦ Search strategies require good understanding of QCD issues
 - ♦ boosted jets and substructure
 - ♦ jet vetoes and resummation techniques
- ♦ Much study: “Handbook of LHC Higgs cross sections”

Challenging perturbative expansion, NNLO required

Anastasiou, Melnikov, Petriello

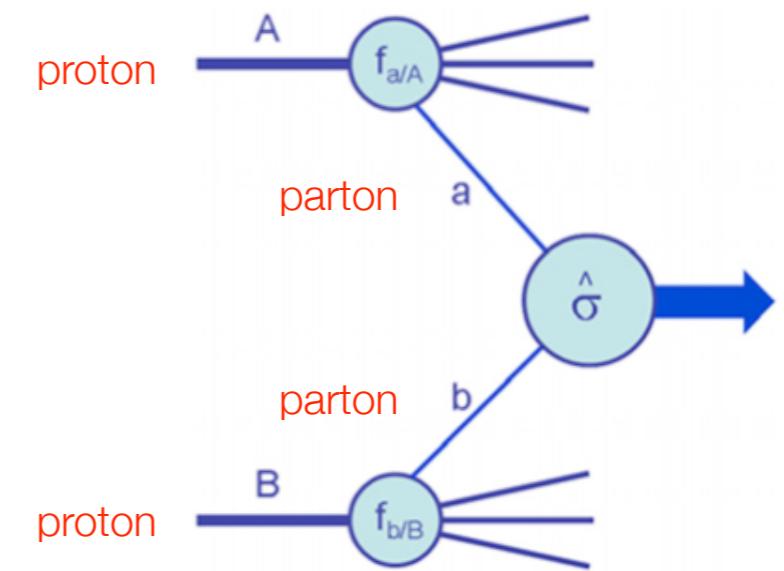


Dittmaier, Mariotti, Passarino, Tanaka

Pdfs and the strong coupling

Pdfs

- ♦ Parton content of the proton:
life-blood of hadron collider physics.



- ♦ Studies in the last year include:

- ♦ assessment of different treatments
of heavy quarks in global pdf analyses

Alekhin, Blumlein, Moch, Kovarik, Stavreva, Kusina, Jezo, Olness, Schienbein, Yu, Thorne

- ♦ uncertainties at large x due to nuclear corrections

Brady, Accardi, Melnitchouk, Owens

- ♦ studies and refinements of established pdf fits

Watt, Thorne, Guzzi, Nadolsky, Lai, Yuan

- ♦ global pdf analyses

Alekhin, Blumlein, Moch, Ball, Bertone, Cerutti,

Del Debbio, Forte, Guffanti, Latorre, Lionetti, Rojo, Ubiali

- ♦ new analysis of HERA data

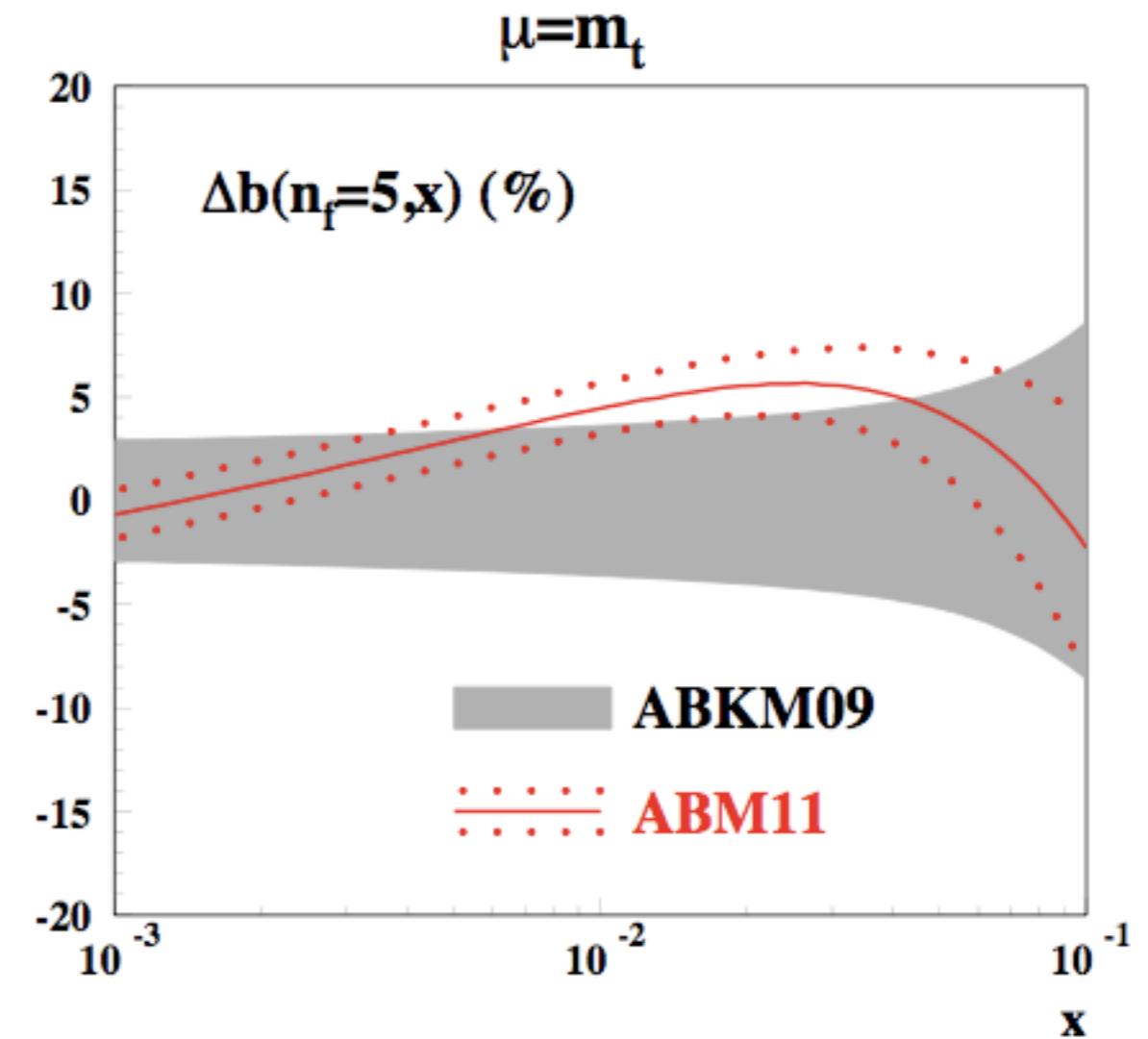
HERAPDF → R. Placakyte parallel

Parton distribution functions

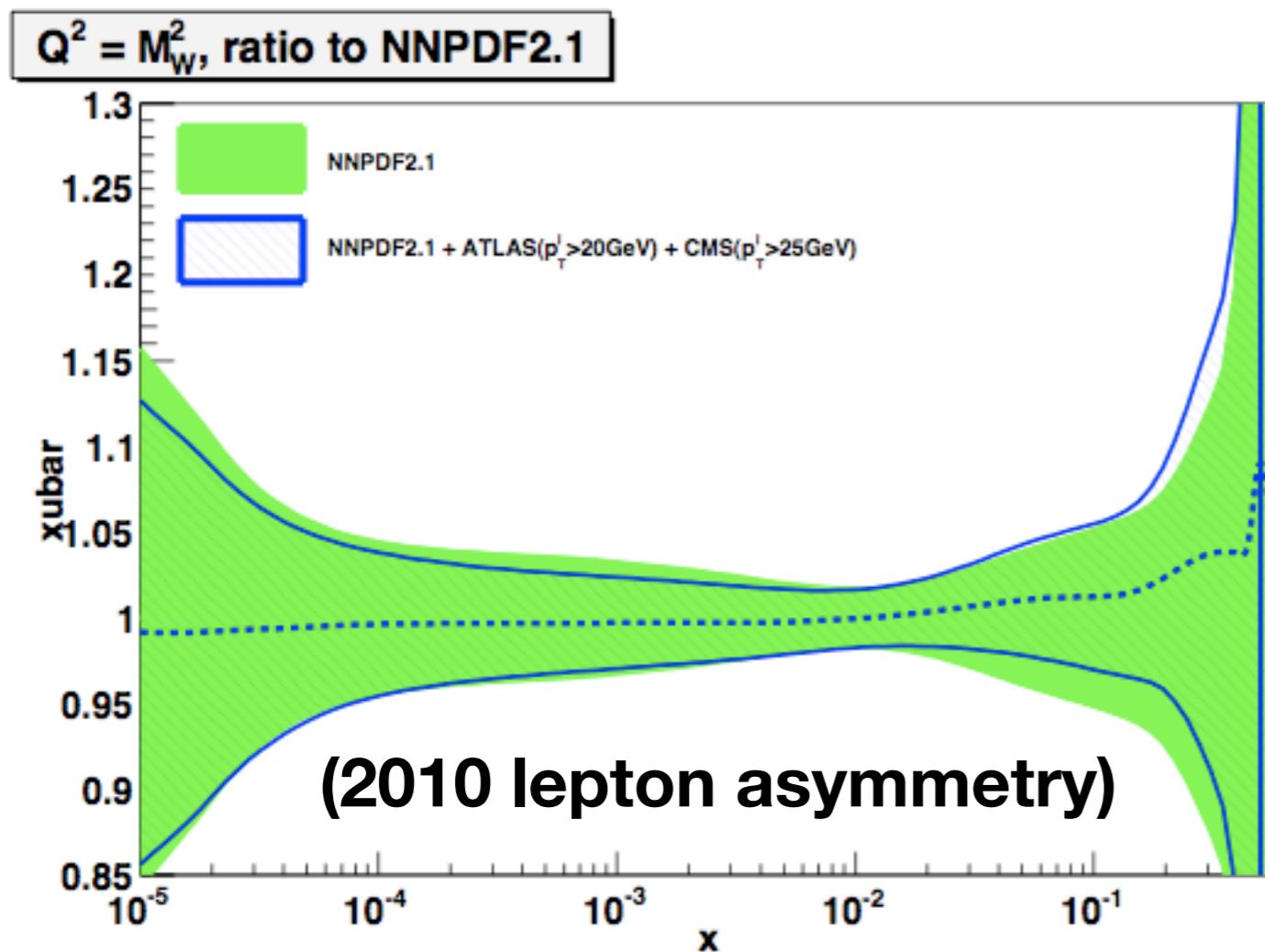
- ◆ Systematic exploration of proton structure at NNLO.
 - ◆ New this year: ABM11 Alekhin, Blumlein, Moch
 - ◆ fit to DIS and fixed-target Drell-Yan data
 - ◆ improved treatment of heavy quarks in DIS, running MS-bar mass
- Alekhin, Moch

b-quark pdf uncertainty

- ◆ much-reduced in ABM11
- ◆ impact on many LHC cross sections (single top, H+b, charged Higgs)



- ♦ Neural net PDF, avoid usual parametrization at input scale
 - ♦ fit includes Tevatron Drell-Yan and inclusive jet data
 - ♦ NNPDF2.1: update to NNLO



Impact of LHC:
NNPDF2.2

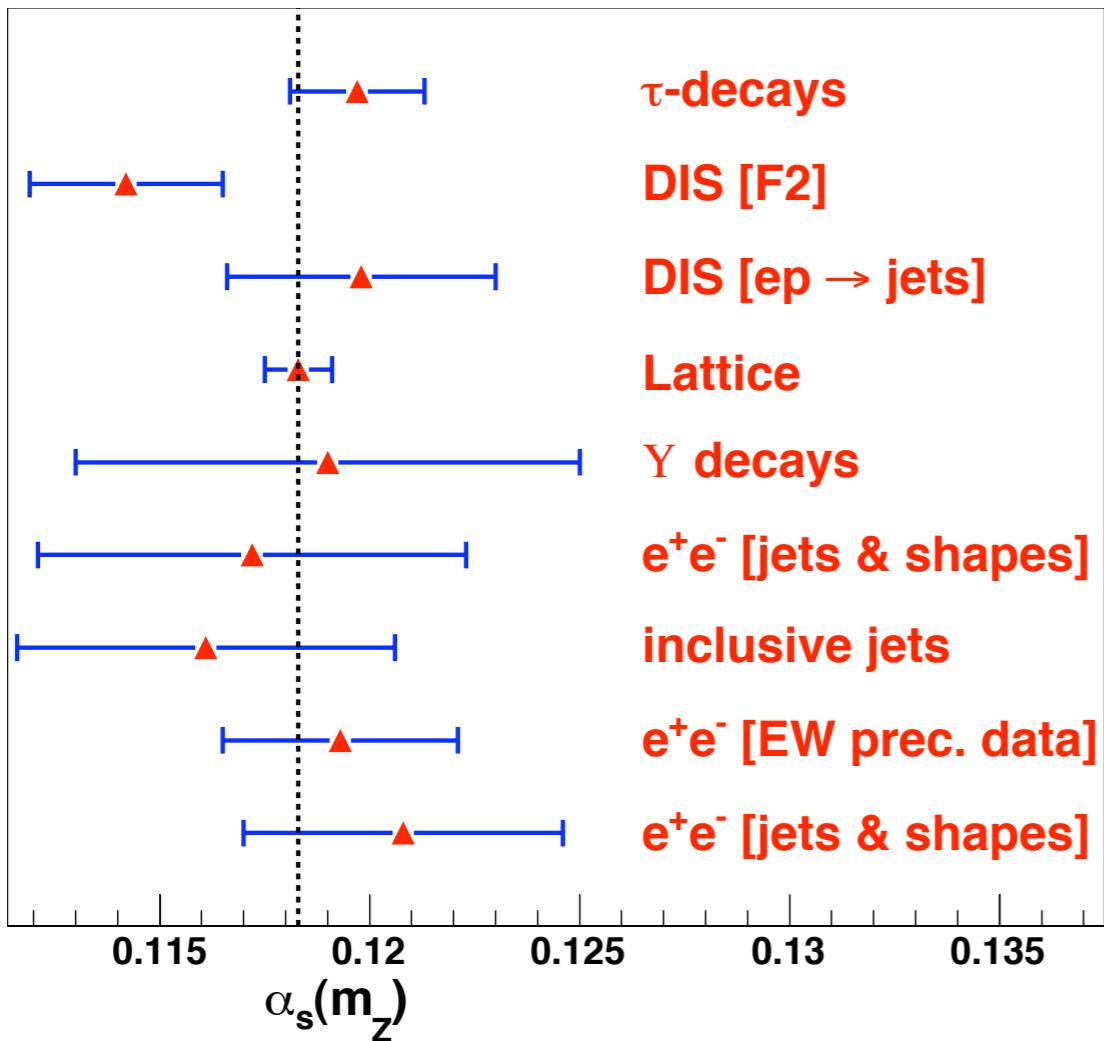
- ♦ Also: top cross section impact on gluon pdf
Beneke et al
- ♦ Very recent: NNPDF2.3

Strong coupling

- ◆ Preliminary world average 2011:

$$\alpha_s(m_Z) = 0.1183 \pm 0.0010$$

S. Bethke, summary of α_s workshop



Strong coupling

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$$\alpha_s(m_Z) = 0.1183 \pm 0.0010$$

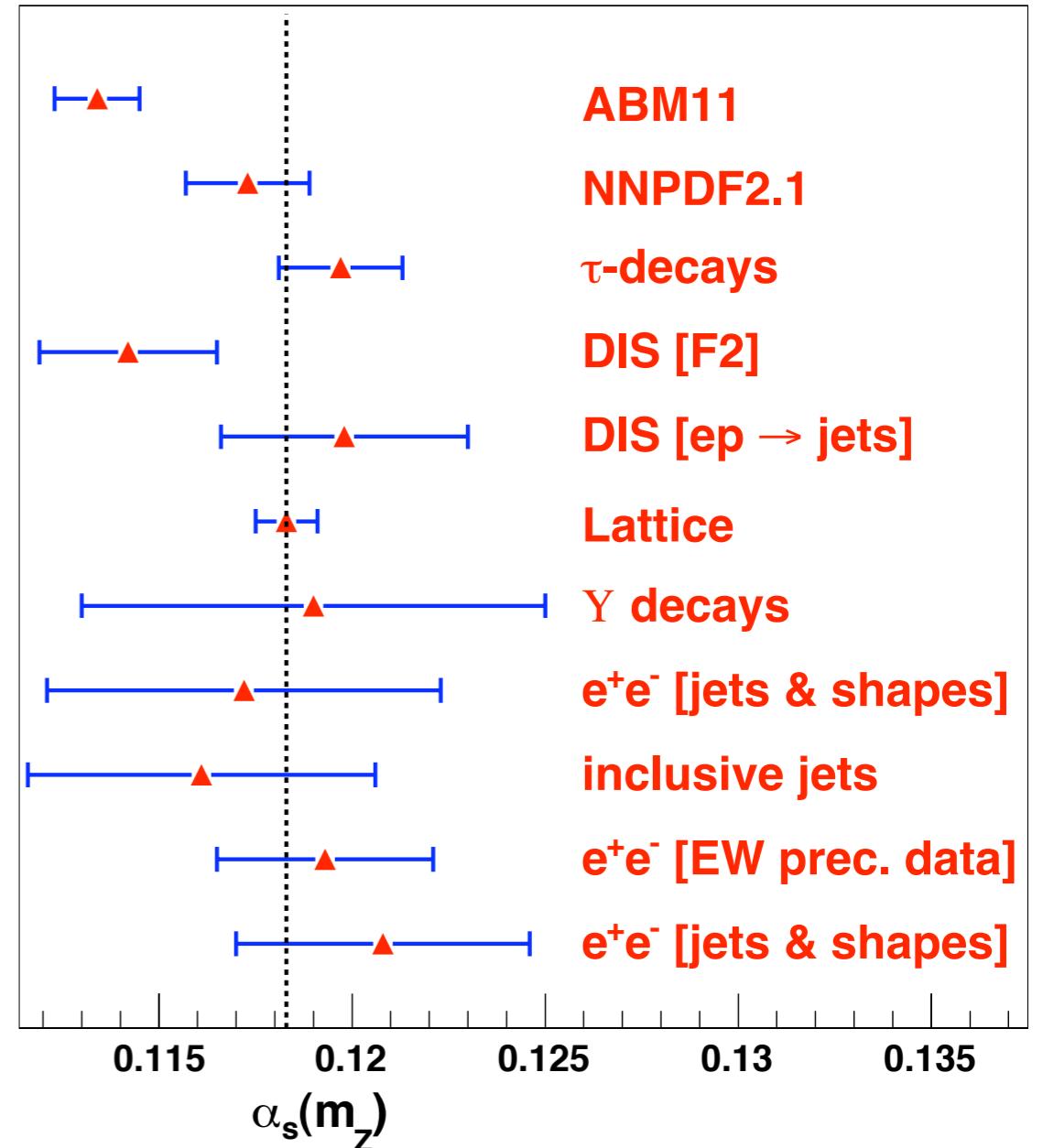
S. Bethke, summary of α_s workshop

- ◆ Simultaneous extraction of strong coupling from NNLO pdf fits:

ABM11 : $\alpha_s(m_Z) = 0.1134 \pm 0.0011$

NNPDF : $\alpha_s(m_Z) = 0.1173 \pm 0.0016$

- ◆ Continued shrinking of errors but tension in central values



Precision calculations

Progress on two fronts

- ♦ Improving predictions for less-understood observables



- ♦ Refining “well-known” calculations, e.g. NLO QCD



- ♦ Both driven by experimental needs and uncertainties

Higgs-related advances

signals

NLO	H+γ+2 jets via VBF	Arnold et al
NLO+PS	gg→H+1,2 jets	Ellis et al
	ttH	Garzelli et al
NNLO	H± t	Klasen et al
	MSSM gg→H	Bagnaschi et al
	WH	Ferrera et al
	H→bb differential rate	Anastasiou et al
	bb→H	Harlander et al, Buehler et al
	non-minimal H via VBF	Bolzoni et al
	non-minimal gg→H	Furlan

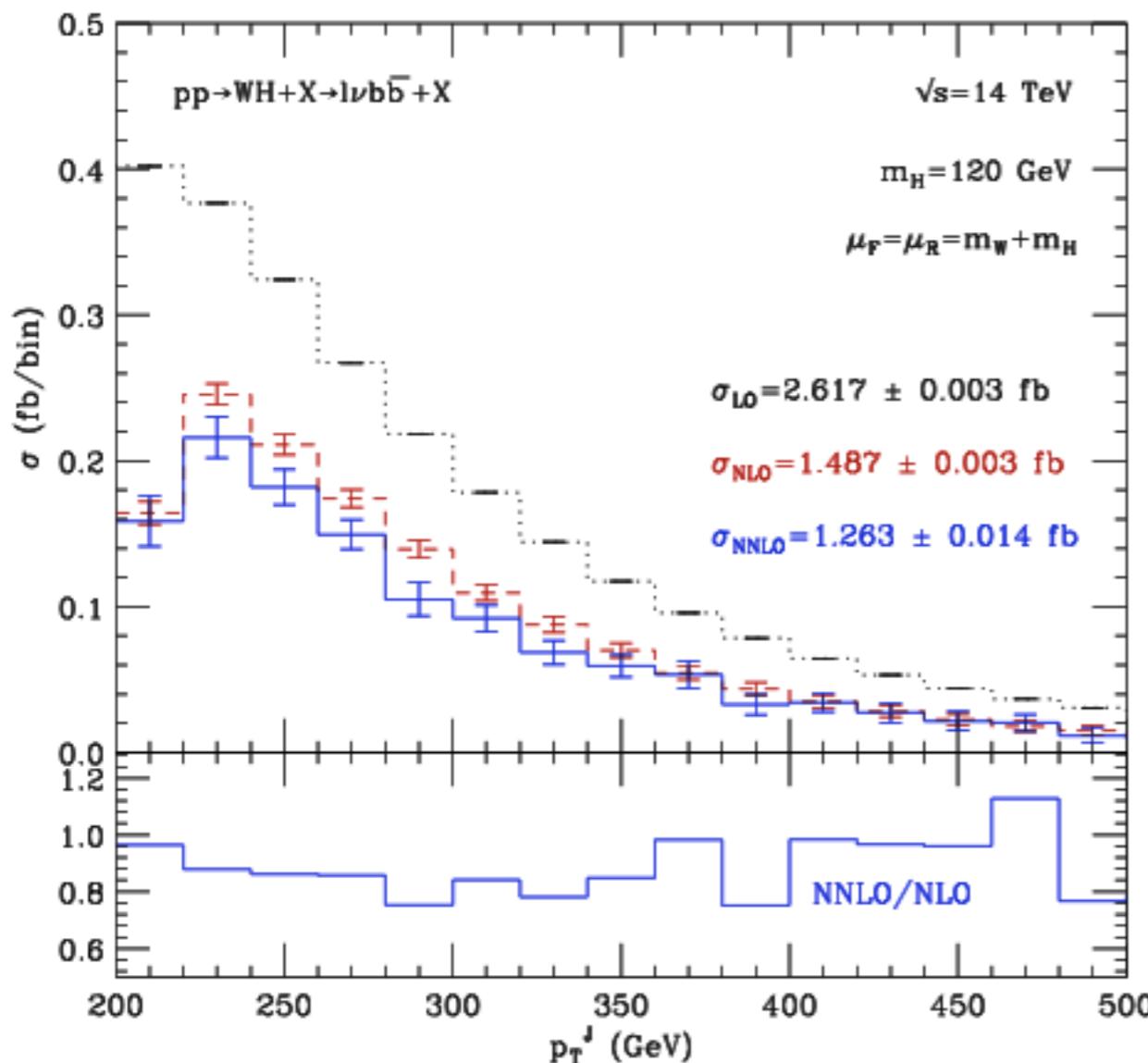
Higgs-related advances

	signals	backgrounds
NLO	H+γ+2 jets via VBF gg→H+1,2 jets ttH H[±]t MSSM gg→H	Arnold et al Ellis et al Garzelli et al Klasen et al Bagnaschi et al
NLO+PS	WH H→bb differential rate bb→H non-minimal H via VBF non-minimal gg→H	Ferrera et al Anastasiou et al Harlander et al, Buehler et al Bolzoni et al Furlan
NNLO		
	WW+jet including gg tt+2 jets ZZ WW,WZ,ZZ Wbb,Zbb Z+2 jets tt+jet YY	Melia et al Bevilacqua et al Frederix et al Melia et al Frederix et al Re, Hamilton et al Alioli, Moch, Uwer Catani et al

Studies for $H \rightarrow b\bar{b}$ decay

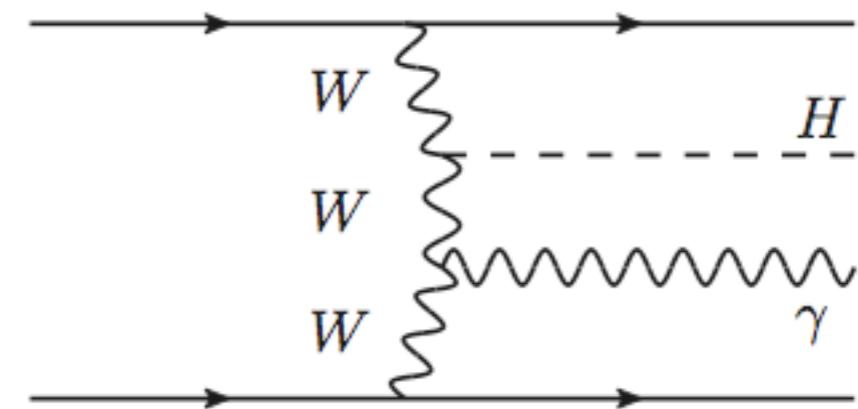
Exclusive NNLO for
WH production

Ferrera et al



NLO for VBF
Higgs+photon

Arnold et al



- ◆ Price of photon emission:
 - ◆ signal $\sim 1/100$
 - ◆ background $\sim 1/3000$
- ◆ Viable cross section $\sim 15\text{fb}$
- ◆ Uncertainties $< 5\text{-}10\%$

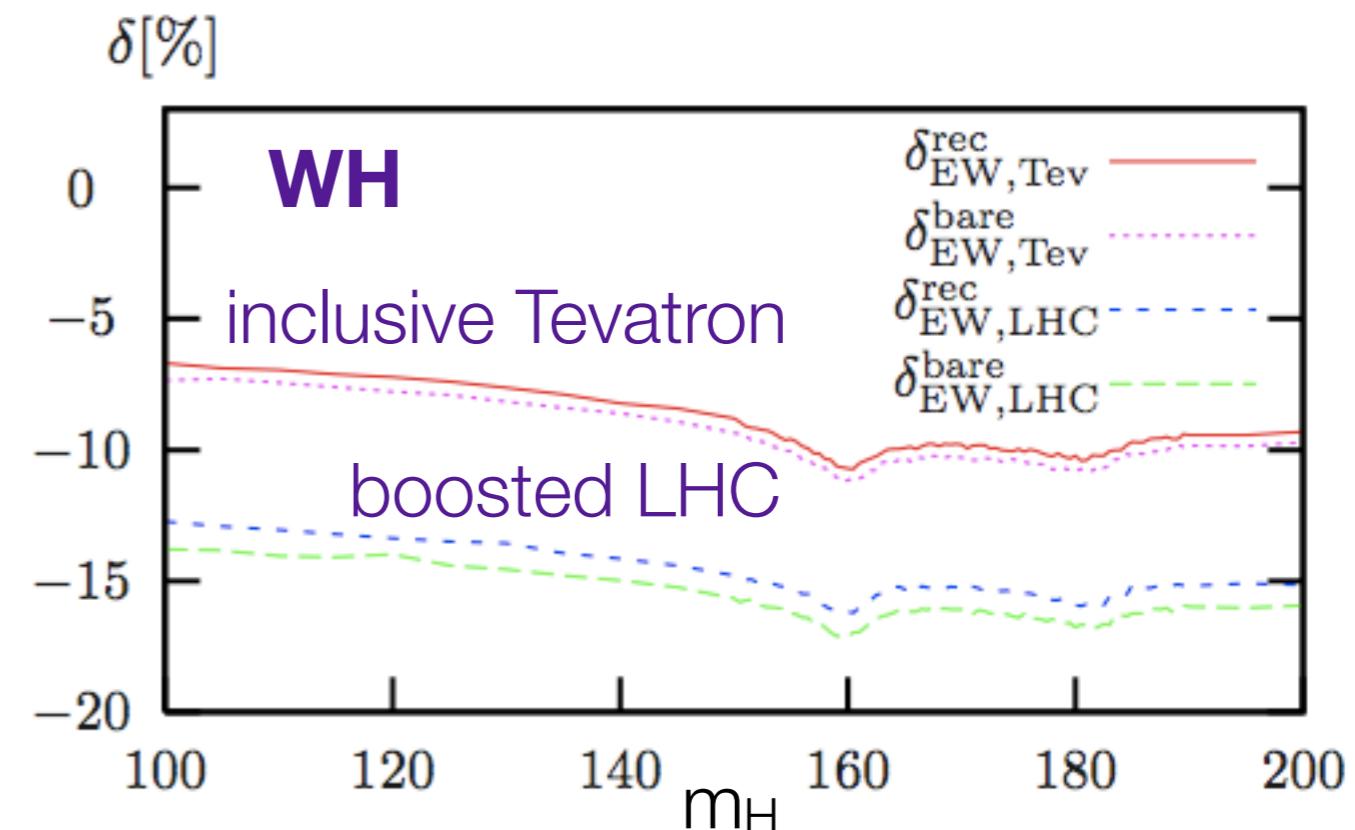
boosted fat jet containing b quarks

Subtle effects

Importance of electroweak corrections

- ◆ crucial role in some kinematic regions

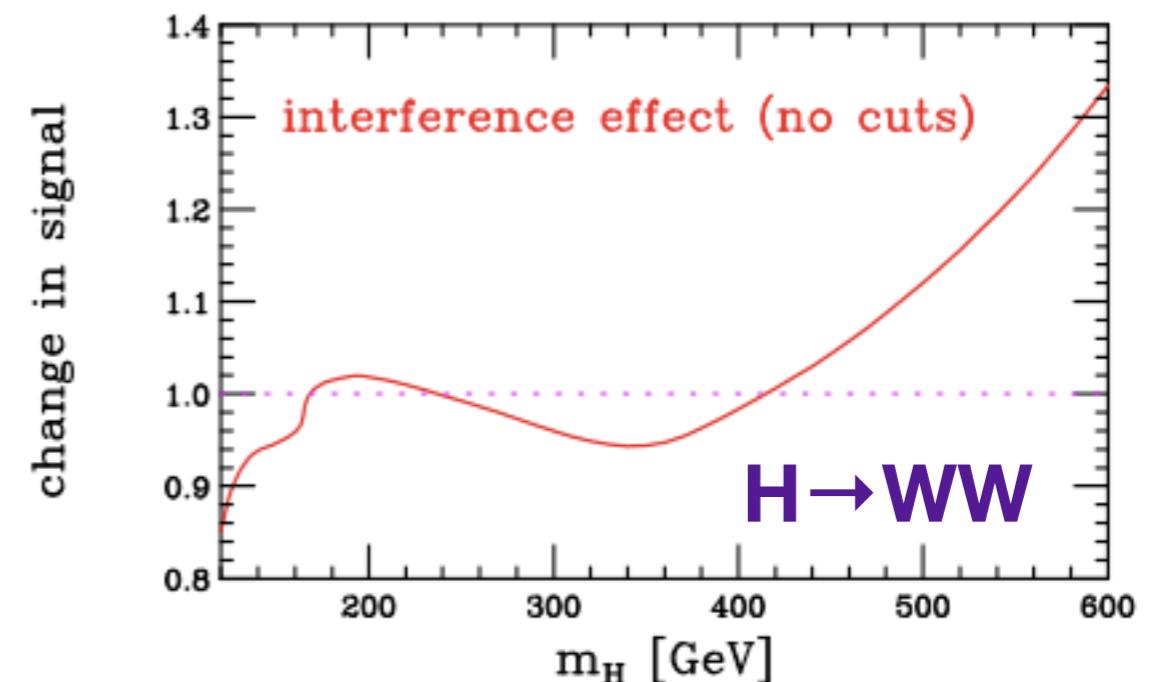
Denner, Dittmaier, Kallweit, Mück



Significant signal/ background interference

- ◆ if intrinsic width large (high m_H)
- ◆ or analysis is sensitive to destructive large \hat{s} tail

Ellis, Williams, JC; Kauer, Passarino

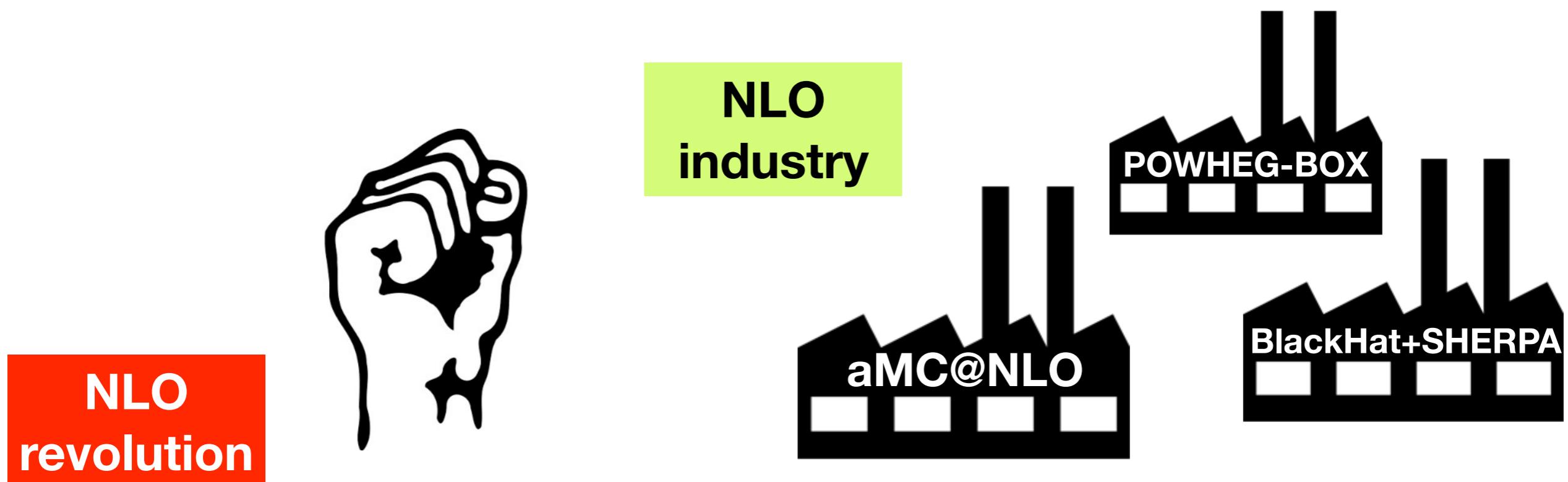


Other NP backgrounds

	W$\gamma\gamma$	Campanario et al	test of EWSB/anom. couplings
	Z$\gamma\gamma, \gamma\gamma\gamma$	Bozzi et al	missing E_T+photons (GMSB)
	ttW	Ellis, JC	same-sign dileptons, trileptons
	4 jets	Ita et al	high mass final states
	Z+4 jets	Ita et al	missing E_T+jets
	Z+2 jets	Re, Hamilton et al	missing E_T+jets
	W+2 jets	Frederix et al	lepton, missing E_T+dijets
	W+1,2,3 jets	Hoche et al	lepton, missing E_T+jets
	W$^+$W$^+$ + 2 jets	QCD/EW Jager, Zanderighi	same-sign dileptons
	ttZ	Garzelli et al	multileptons

The Industrial Age of NLO

- ♦ In recent years, much reference to “NLO revolution”
 - ♦ development of new wave of tools in anticipation of LHC
 - ♦ especially numerical techniques: straightforward generation of new results for complicated final states
- ♦ 2011-12: time for putting these revolutionary ideas to work



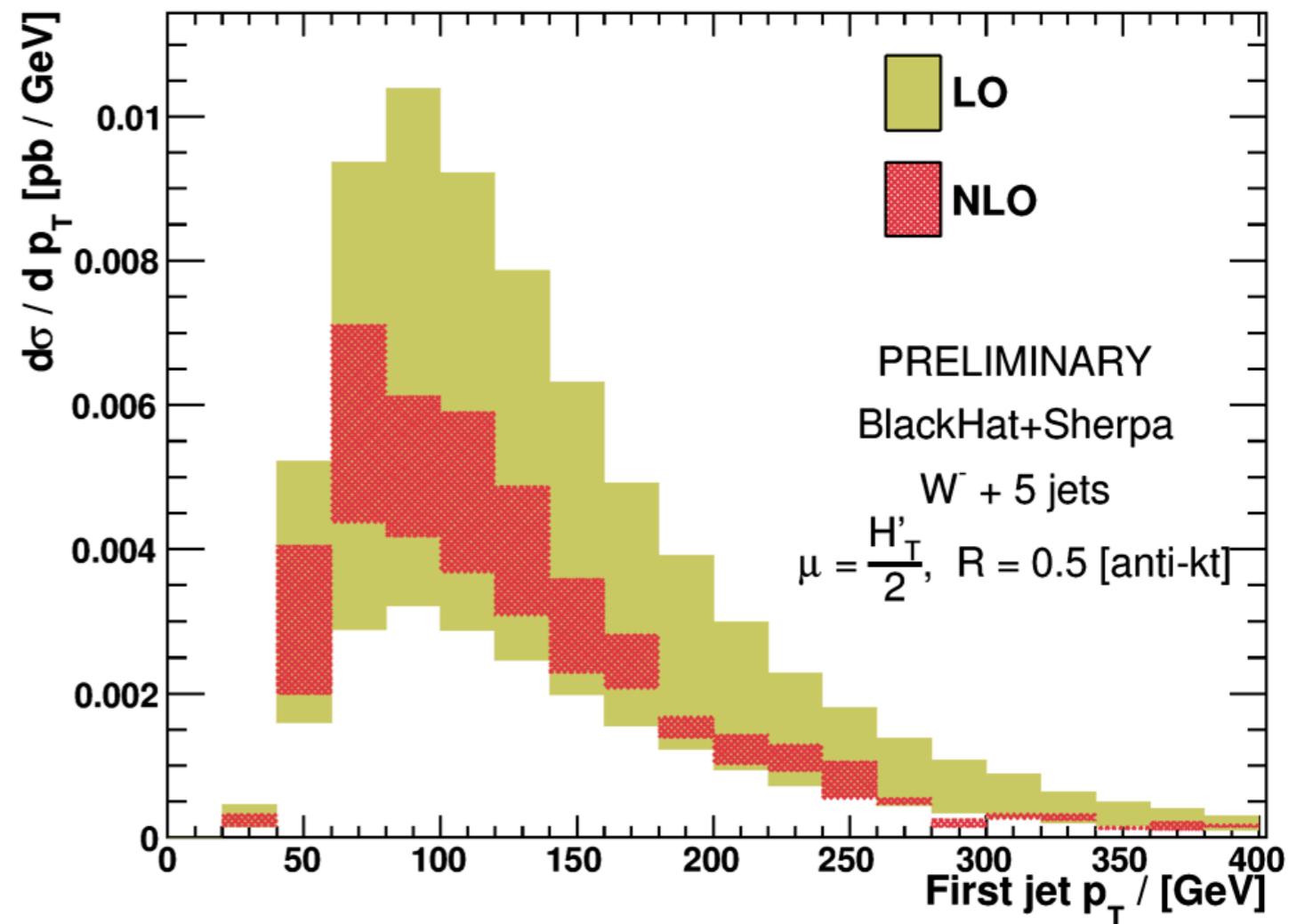
Blackhat+SHERPA

Bern, Diana, Dixon, Febres Cordero,
Höche, Ita, Kosower, Maître, Ozeren

- ♦ The frontier of NLO complexity
→ L. Dixon, D. Kosower parallel
- ♦ on-shell methods for loops, BlackHat
- ♦ real emission, SHERPA
- ♦ in the last year:
 - ♦ four-jet production
 - ♦ Z+4 jets

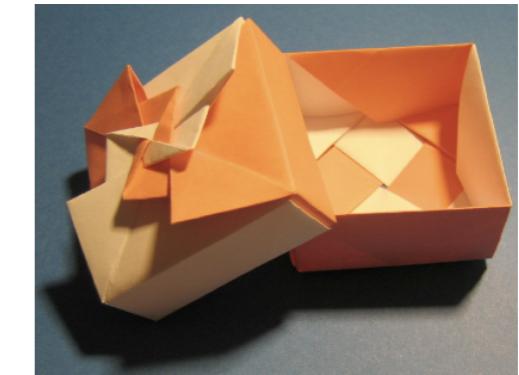
New @ ICHEP:
W+5 jets

→ D. Kosower parallel



POWHEG-BOX

- ◆ Package for theorists to merge any NLO calculation with parton shower



Alioli, Nason, Oleari, Re, Frixione

- ◆ Banner year for new predictions

$H \pm t$ Klasen et al

$gg \rightarrow H + 1, 2 \text{ jets}$ Ellis et al

MSSM $gg \rightarrow H$ Bagnaschi et al

$t\bar{t}H$ Garzelli et al

$t\bar{t}Z$ Garzelli et al

WW, WZ, ZZ Melia et al

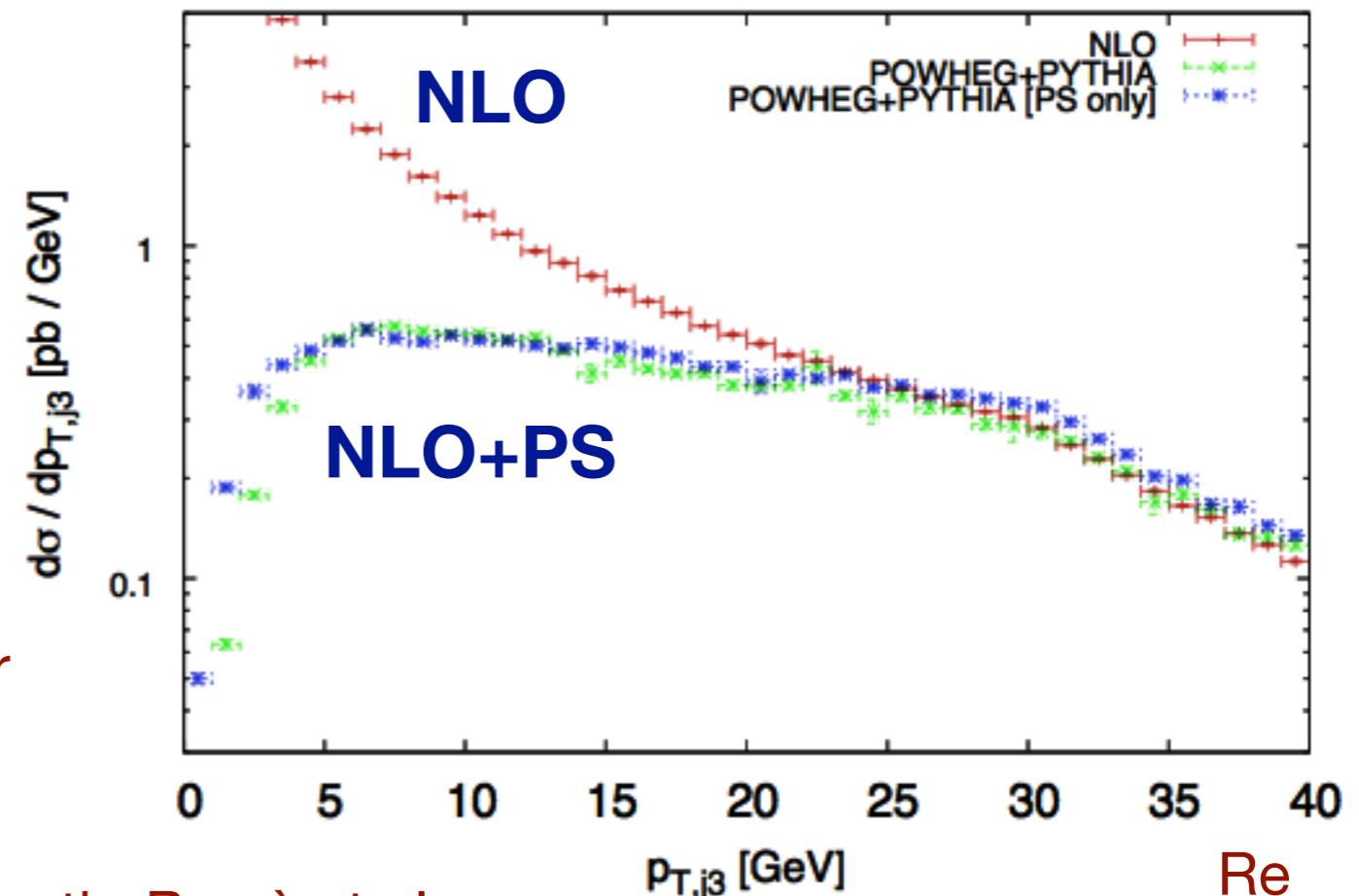
$t\bar{t} + \text{jet}$ Alioli, Moch, Uwer

$Z + 2 \text{ jets}$ Re

W QCD/EW Bernaciak, Wackerlo; Barzè et al

$W^+W^++2 \text{ jets}$ QCD/EW Jager, Zanderighi

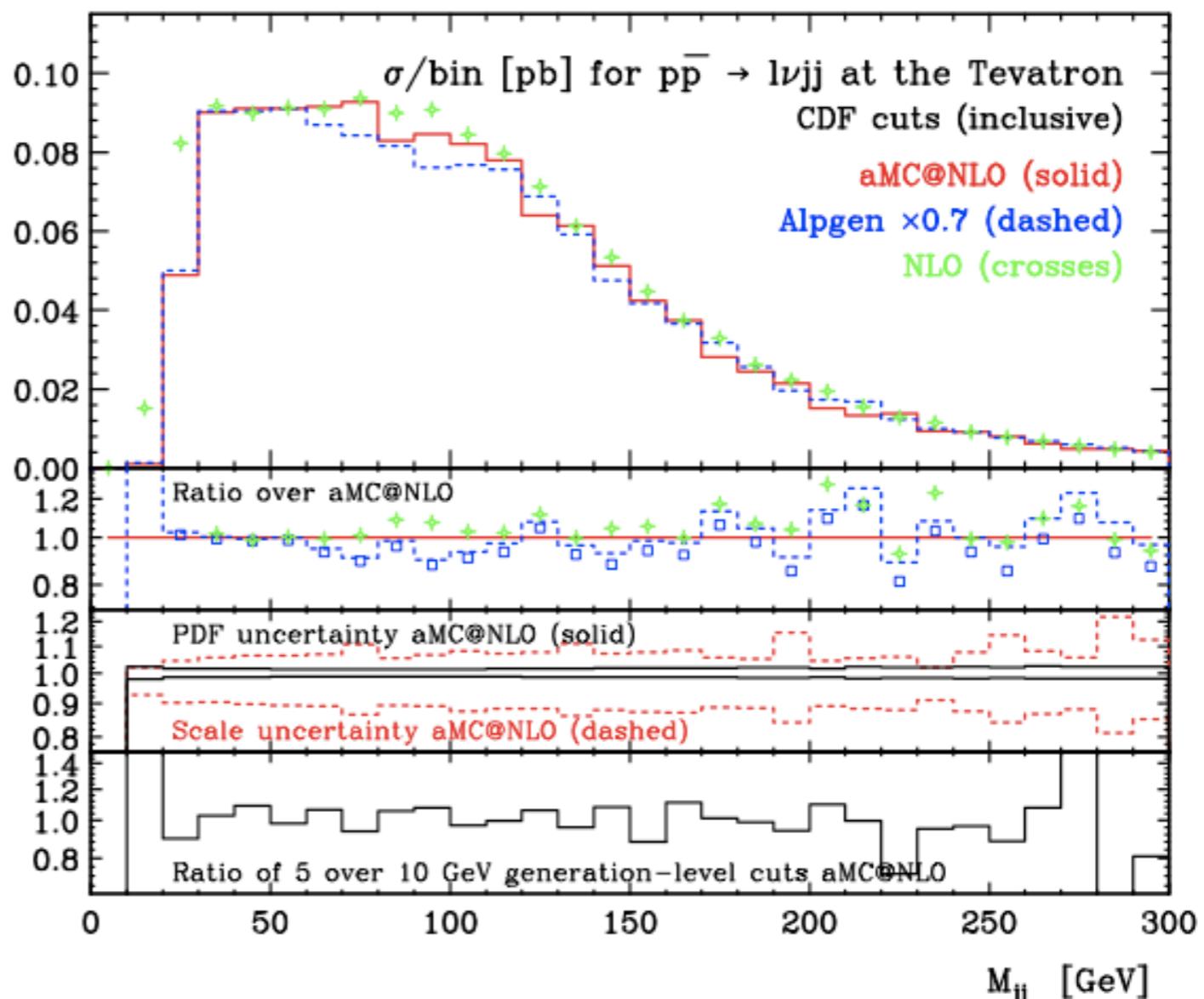
3rd jet p_T in $Z+2$ jets



- ◆ Generation of NLO+PS predictions in an automated fashion
- ◆ 2011-12: first full phenomenology in this approach.

W+2 jets study:
PS vs NLO vs NLO+PS

- ◆ Also this year:
 - ◆ 4-lepton production
 - ◆ Wbb, Zbb



SHERPA

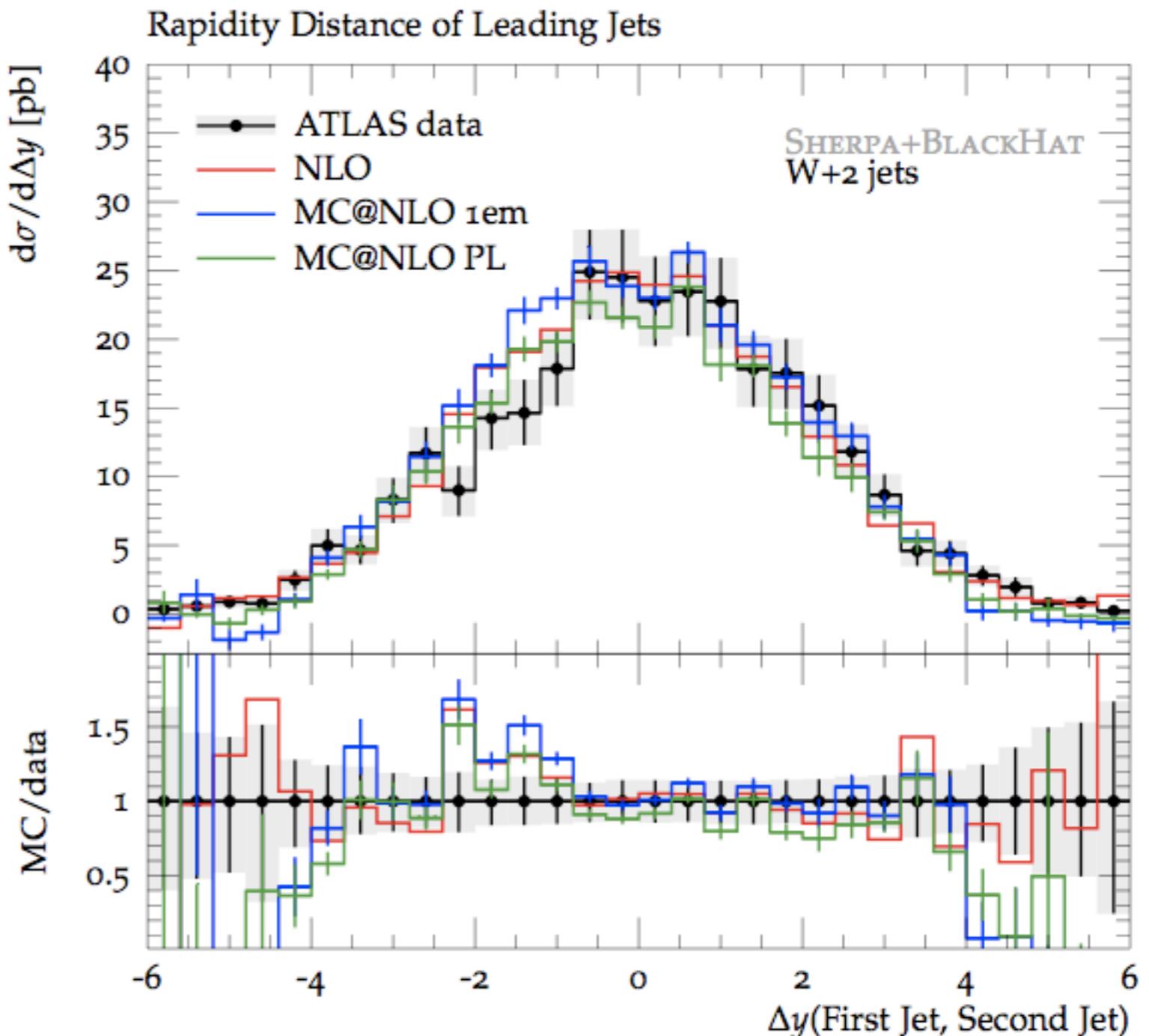
- ♦ Implementation of MC@NLO procedure in SHERPA.

- ♦ Application to W+1,2,3 jets using BlackHat MEs.

Höche, Krauss,
Schönherr, Siegert

- ♦ Smooth interpolation between POWHEG and MC@NLO type procedures

→ M. Schönherr parallel

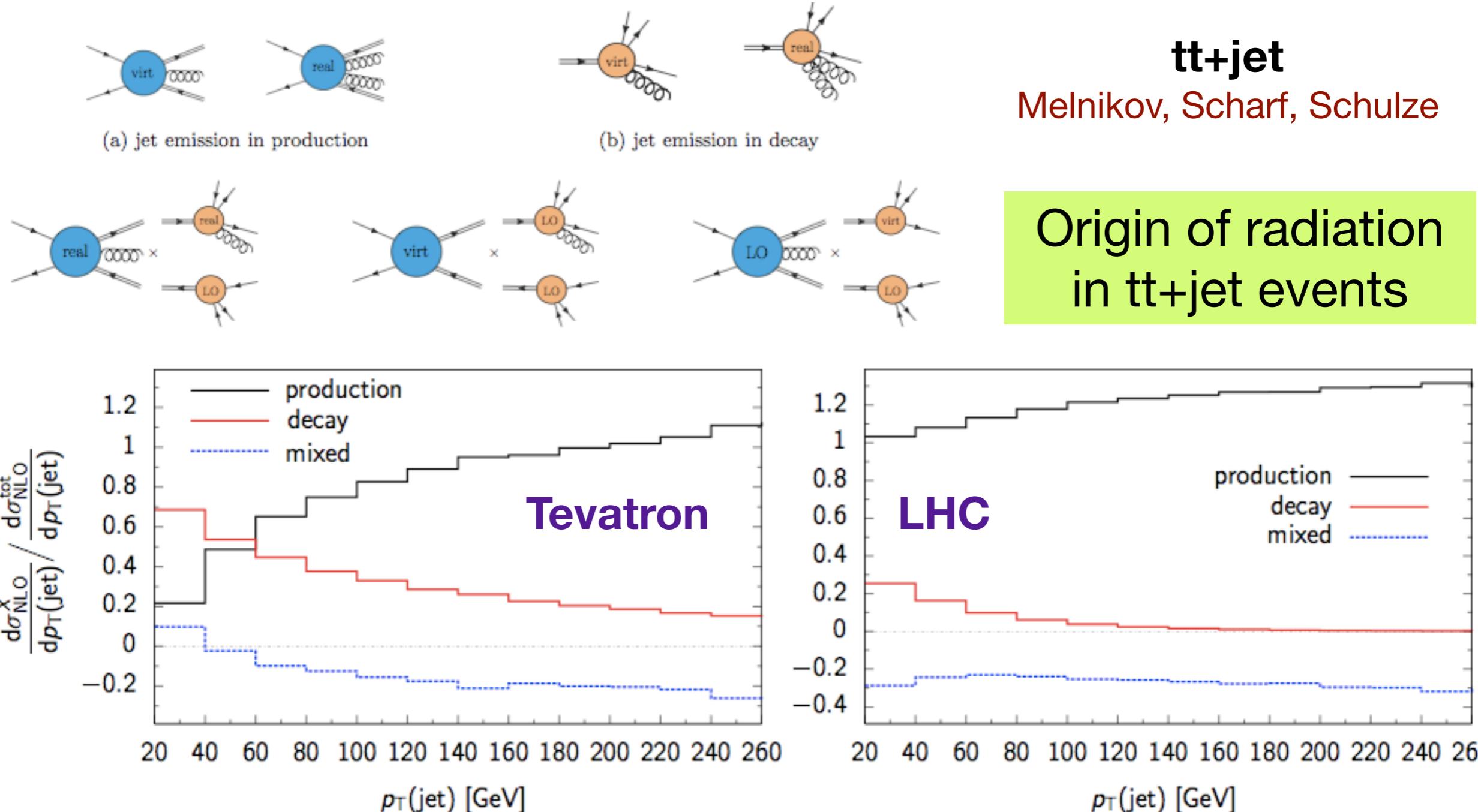


Parton level NLO

- ♦ No parton shower - yet.
- ♦ Automated 1-loop approaches
 - ♦ HELAC-NLO: tt+2 jets, tttt Bevilacqua, Czakon, Papadopoulos, Worek
 - ♦ GoSam: WW+2 jets
Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
- ♦ Other calculations:
 - ♦ VBFNLO: H γ by VBF, Z $\gamma\gamma$, $\gamma\gamma\gamma$, W $\gamma\gamma$ +jet
Arnold, Bozzi, Campanario, Englert, Figy, Jager, Rauch, Zeppenfeld
 - ♦ MCFM: ttW, WW by gg box Ellis, Williams, JC
 - ♦ MCFM+: WW+jet including gg box Melia, Melnikov, Rontsch, Schulze, Zanderighi
 - ♦ tt+jet: radiation in top decay Melnikov, Scharf, Schulze

Top quark production and decay

- ◆ Small width $\Gamma_t/m_t < 1\%$ → factorization of production and decay



Lesson: radiation in decay important

An orthogonal approach

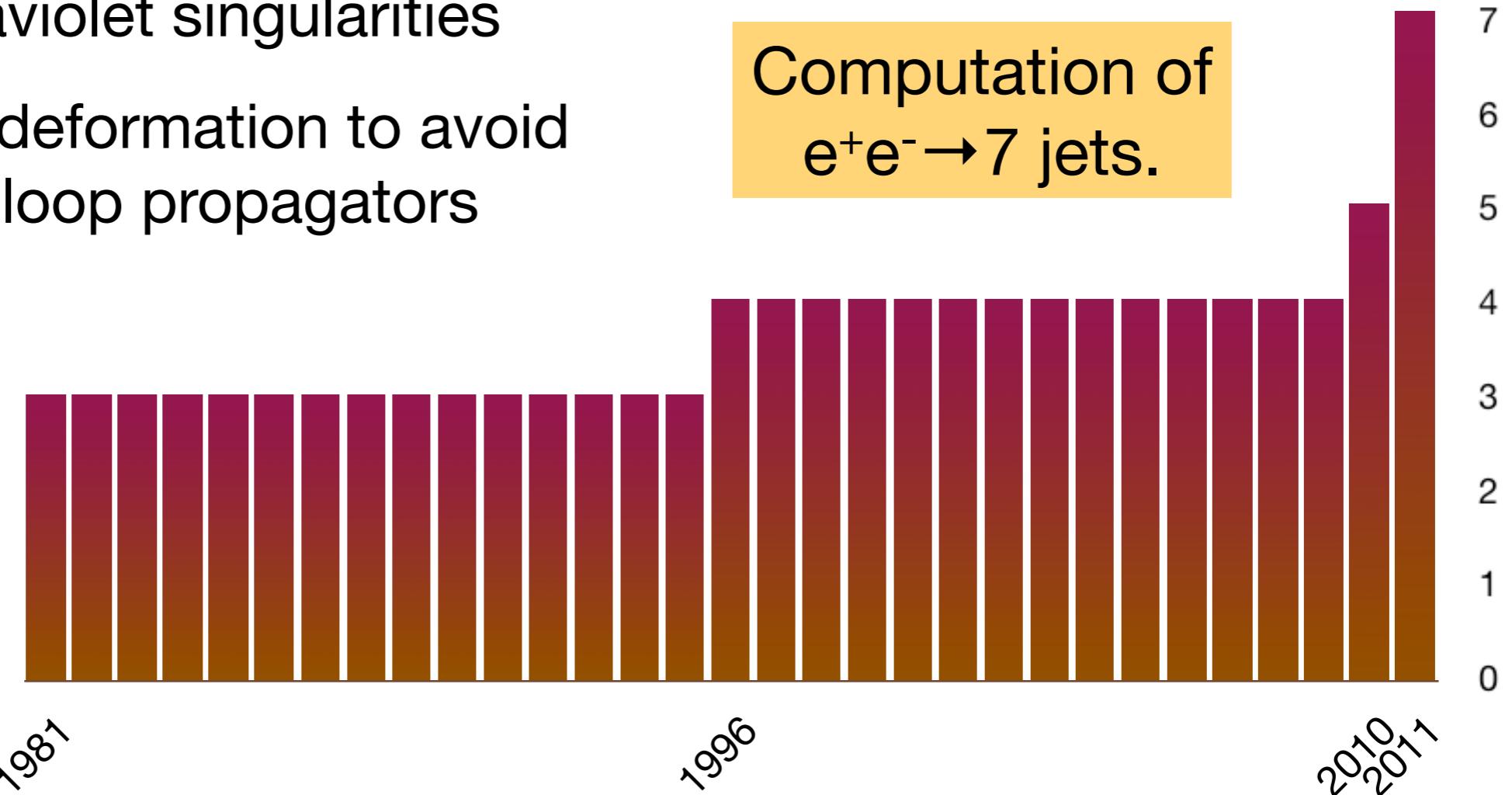
Becker, Goetz, Reuschle,
Schwan, Weinzierl

- ♦ Perform loop integral numerically

$$A_{\text{bare}}^{(1)} = \int \frac{d^D k}{(2\pi)^D} G_{\text{bare}}^{(1)}, \quad G_{\text{bare}}^{(1)} = P_a(k) \prod_{j=1}^n \frac{1}{k_j^2 - m_j^2 + i\delta}.$$

- ♦ local subtractions for infrared and ultraviolet singularities
- ♦ contour deformation to avoid on-shell loop propagators

$e^+e^- \rightarrow n$ jets.



Parton showers

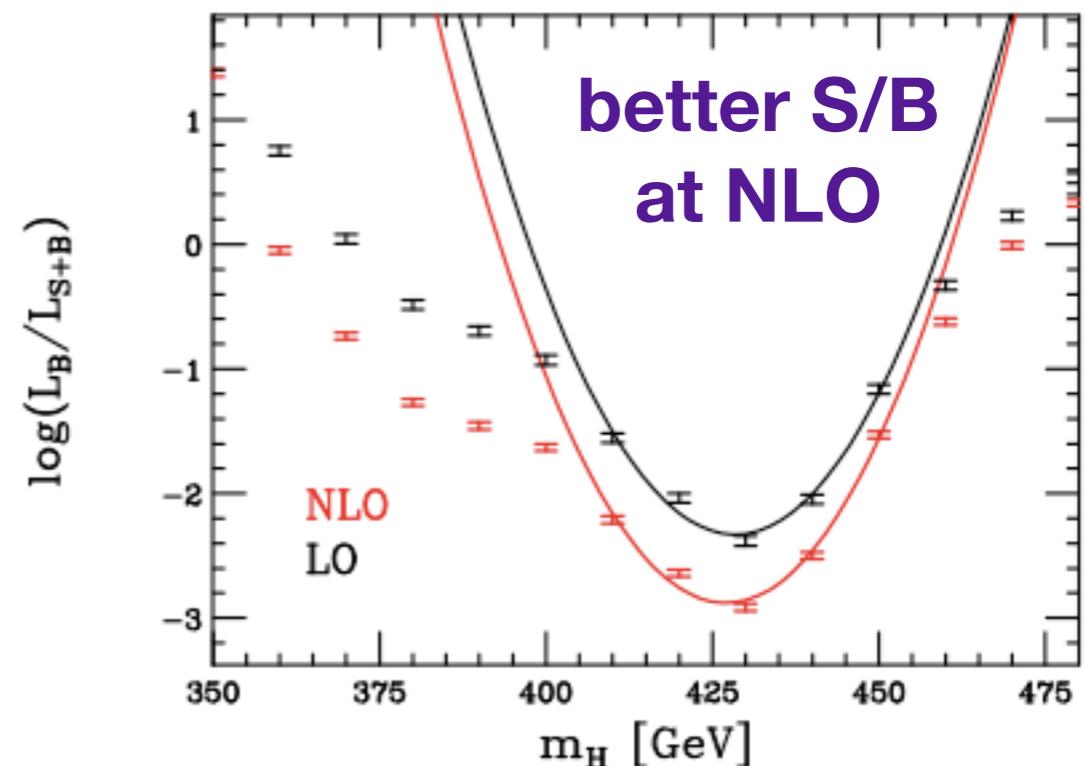
- ♦ Most of the focus on merging NLO and PS
 - ♦ HERWIG++ d'Errico, Richardson, Platzer, Gieseke
- ♦ Other work this year:
 - ♦ improving consistency of MLM matrix element matchingCooper, Katzy, Mangano, Messina, Mijovic, Skands
 - ♦ VINCIA: more efficient matching and massive fermionsLopez-Villarejo, Skands, Gehrmann-de Ridder, Ritzmann
 - ♦ HERWIG++: MPI, color reconnection studiesGieseke, Rohr, Siodmok
 - ♦ PYTHIA8: implementation of CKKW-L merging scheme for NLO calculationsLönnblad, Prestel
→ L. Lönnblad parallel

New directions for NLO

Extension of matrix-element
method to NLO accuracy

Giele, Williams, JC

- ◆ most efficient extraction of model parameters



New directions for NLO

Extension of matrix-element
method to NLO accuracy

Giele, Williams, JC

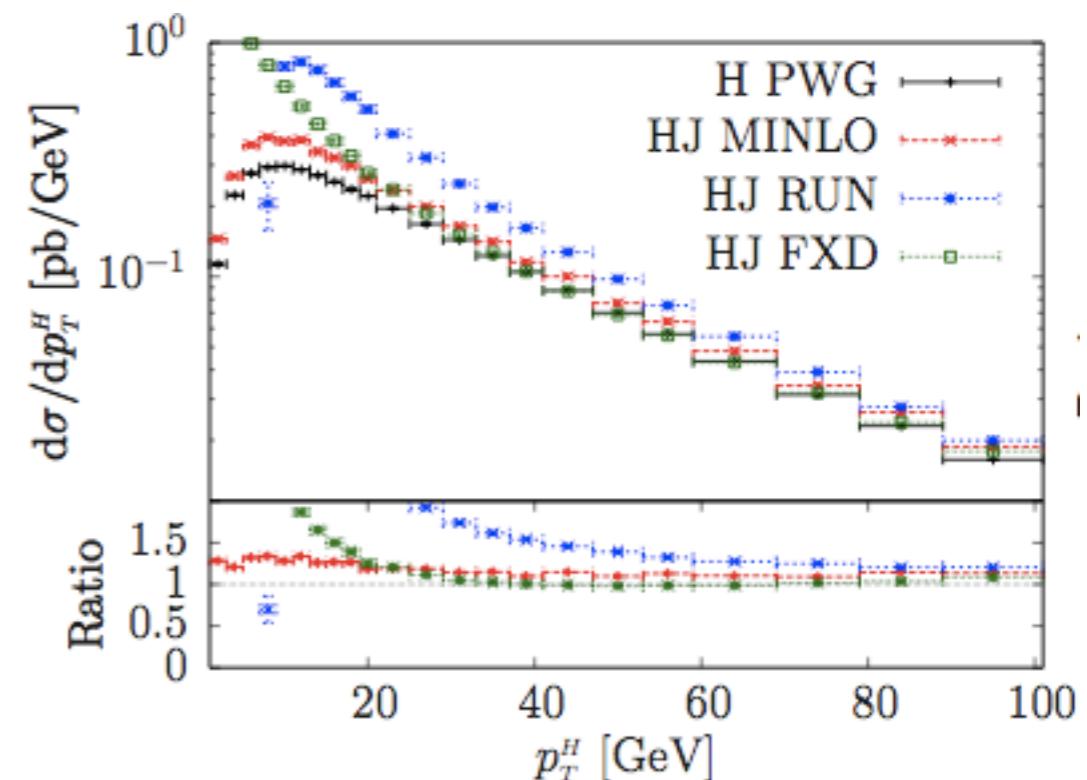
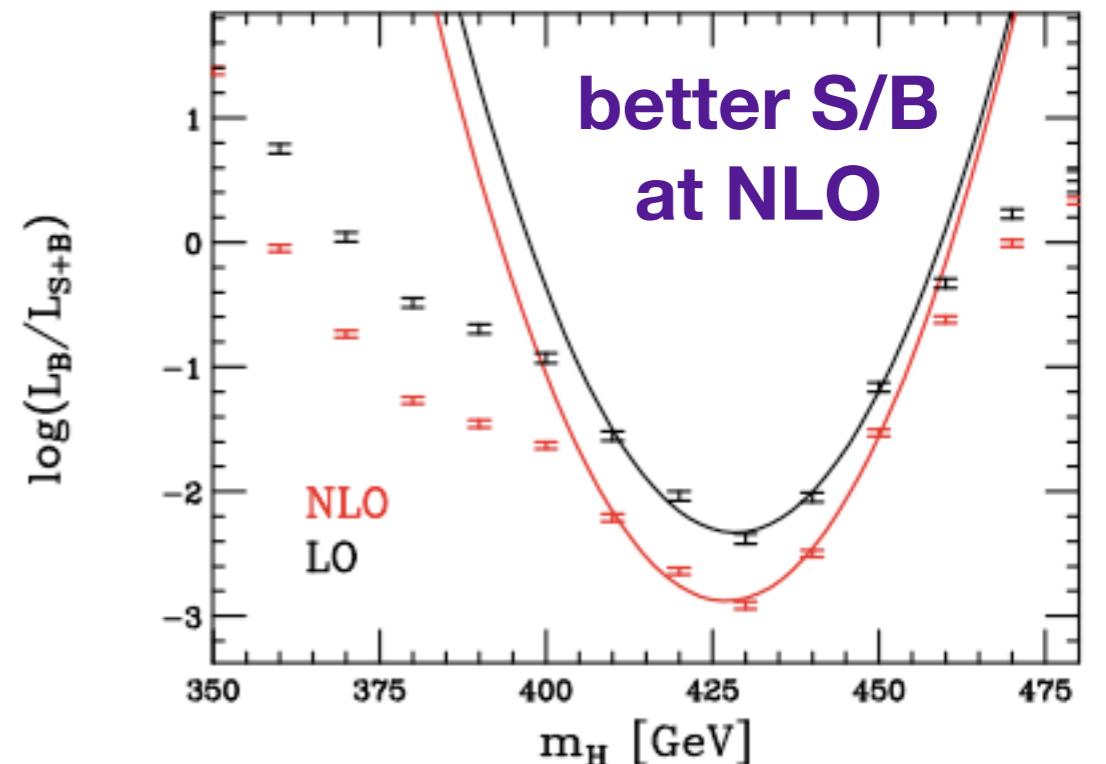
- ◆ most efficient extraction of model parameters

Better scale setting in NLO calculations

Hamilton, Nason, Zanderighi

- ◆ similar to existing methods in tree level ME/PS merging

**improved description
outside usual NLO region**



NNLO in the pipeline

- ♦ Ingredients for fully differential NNLO

- ♦ subtraction terms

Herzog, Gehrmann-de Ridder, Glover, Pires, Boughezal,
Melnikov, Petriello, Currie, Gehrmann, Monni

- ♦ new 2-loop amplitudes for $H \rightarrow 3$ partons and $q\bar{q} \rightarrow W\gamma, Z\gamma$

Gehrmann, Jaquier, Glover, Koukoutsakis, Tancredi

- ♦ extension of unitarity methods to two loops

Badger, Frellesvig, Zhang; Mastrolia, Ossola; Larsen, Johansson, Kosower
→ D. Kosower parallel

- ♦ Threshold resummation for $W/Z/H$ production NNLL,NNLO.

Becher, Bell, Marti; Gonsalves, Kidonakis
→ N. Kidonakis parallel

Top production

NNLO corrections to $qq \rightarrow tt$

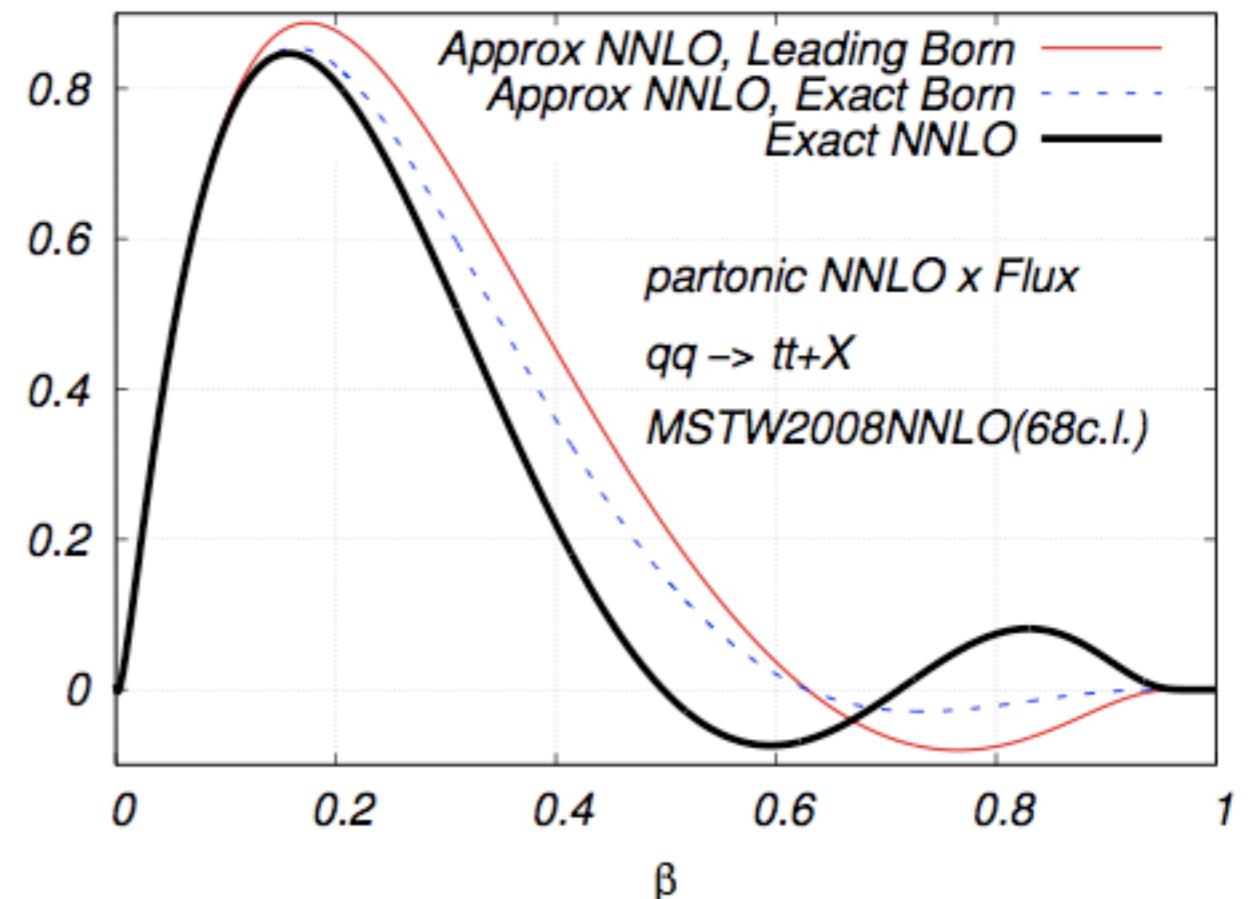
Barnreuther, Czakon, Mitov

- ♦ First ever NNLO calculation for a hadron collider with two (massive) colored partons in the final state
- ♦ Cross section in terms of top quark rel. velocity $\beta = \sqrt{1 - 4m^2/s}$:

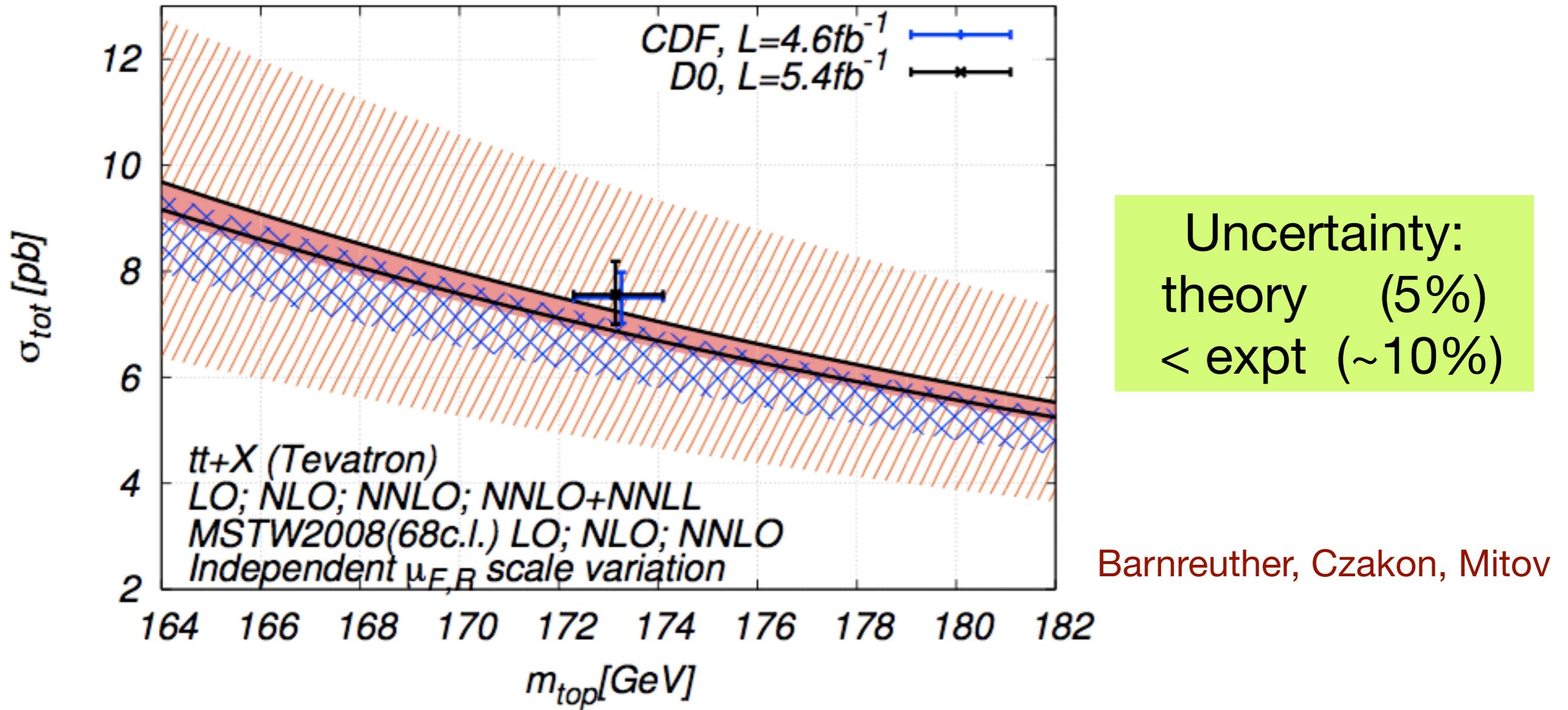
$$\sigma_{\text{tot}} = \sum_{i,j} \int_0^{\beta_{\text{max}}} d\beta \Phi_{ij}(\beta, \mu^2) \hat{\sigma}_{ij}(\beta, m^2, \mu^2)$$

Exact NNLO vs.
threshold approximation

- ♦ small β approx. superseded
- ♦ Threshold approximation poor over most of the range
- ♦ less difference in integral



Impact of NNLO+NNLL at Tevatron

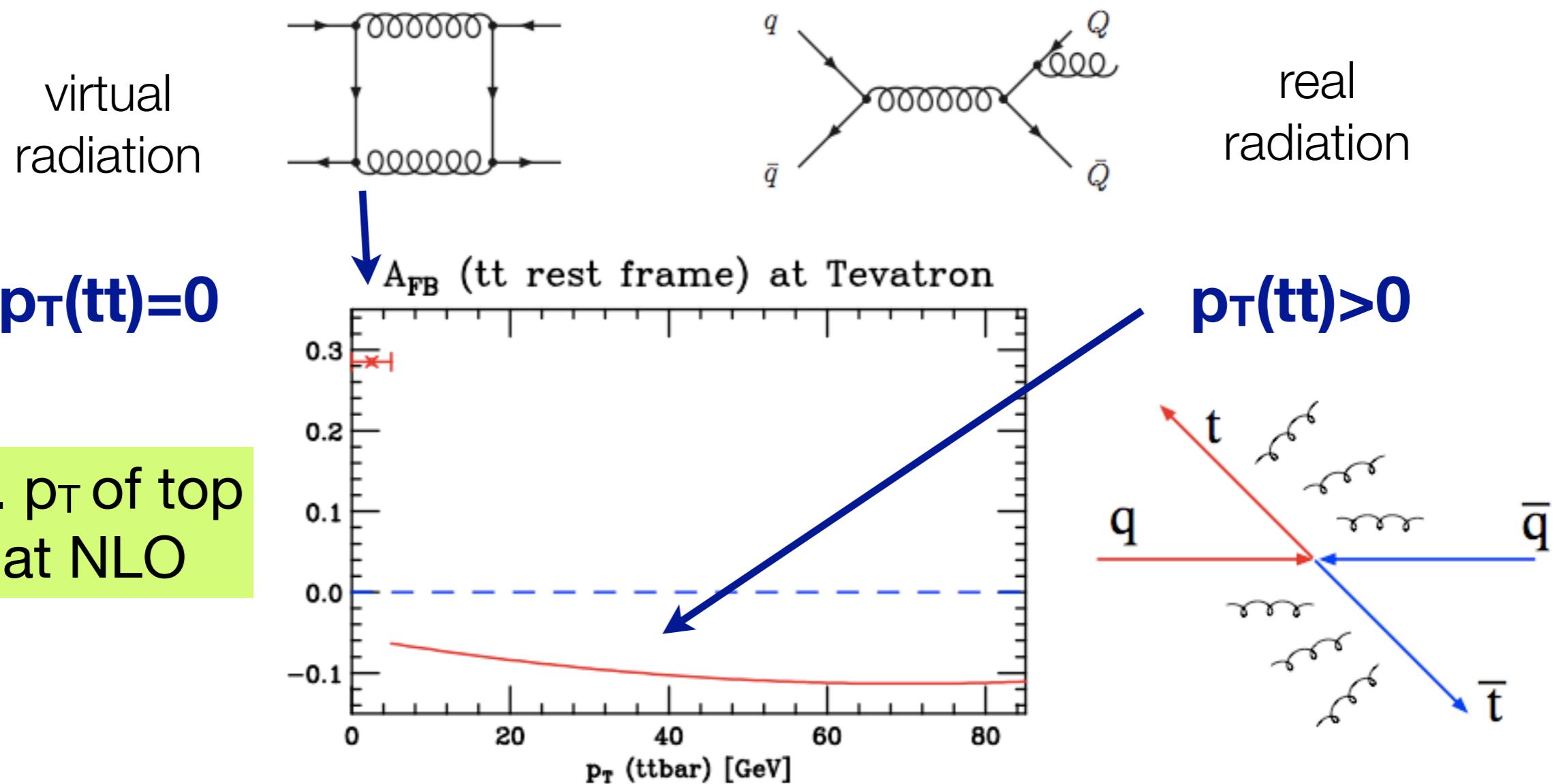


♦ Combined NNLO+NNLL threshold resummation

Langenfeld, Moch, Uwer, Ahrens, Ferroglia, Neubert, Pecjak, Yang, Kidonakis, Beneke, Falgari, Klein, Schwinn, Cacciari, Czakon, Mangano, Mitov, Schwinn

Top asymmetry at the Tevatron

- ◆ Prediction at LO: no forward-backward asymmetry
- ◆ Positive asymmetry arises at NLO in QCD



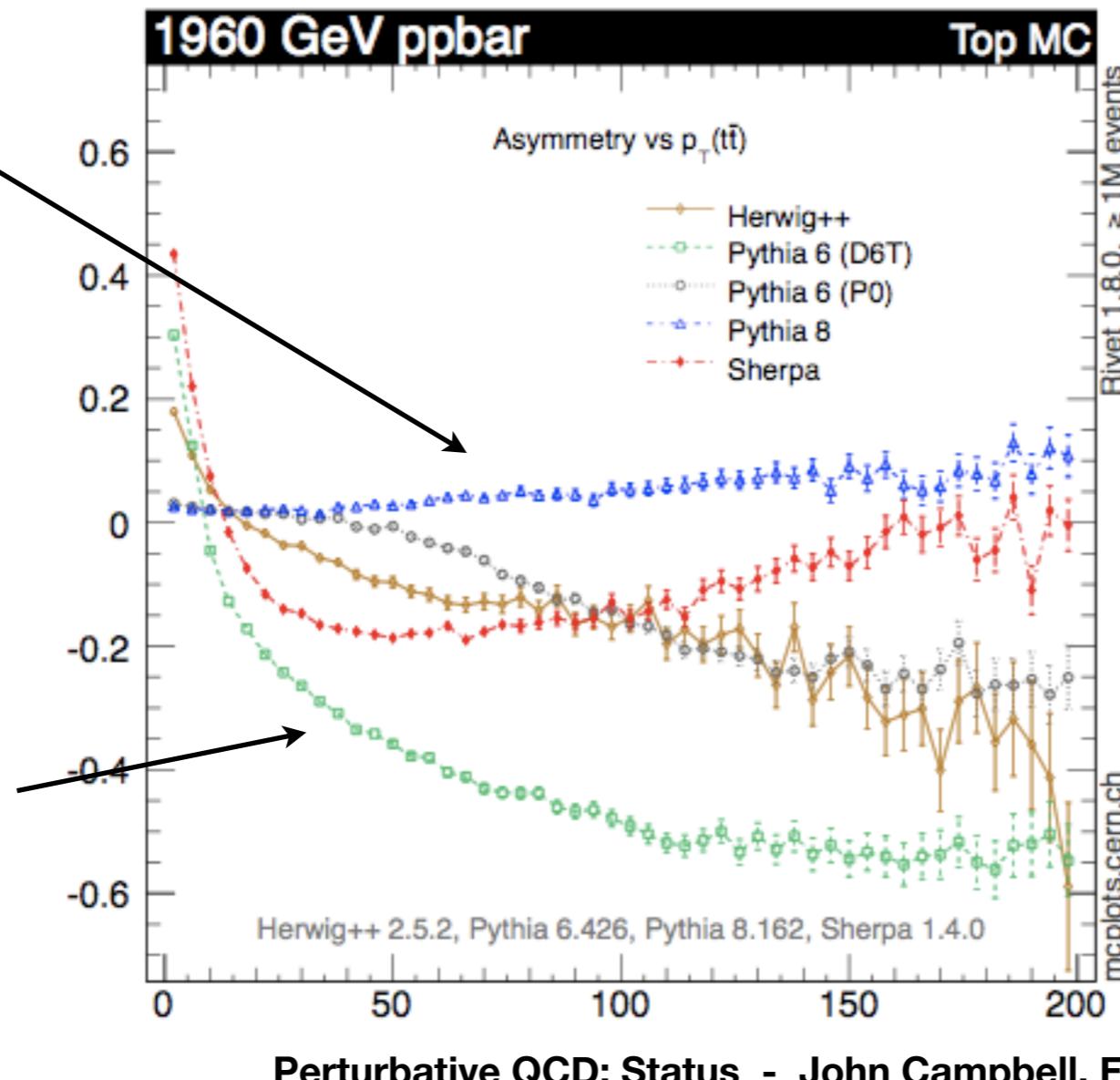
Parton shower asymmetry

Skands, Webber, Winter

- ♦ Detailed investigation of asymmetry in parton showers
 - ♦ effect built-in through color-coherence of most showers
 - ♦ over-estimate due to large N_c : $\left(\frac{N_c^2 - 4}{N_c}\right)_{\text{exact}} \rightarrow \left(\frac{N_c^2 - 1}{N_c}\right)_{\text{MC}}$

coherence not
yet implemented

color coherence
over-estimated

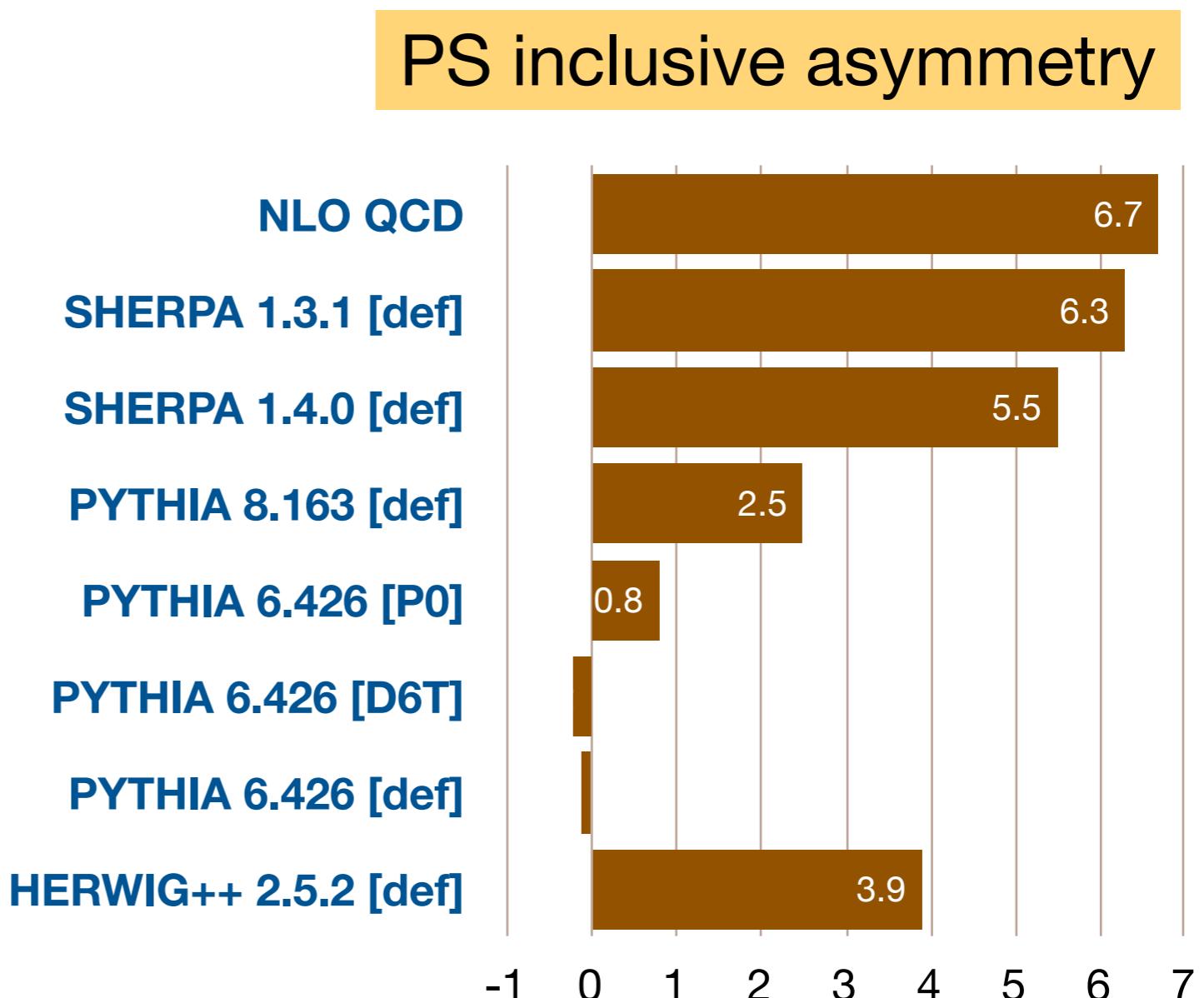


A_{FB} vs. p_T of
top pair for PS
predictions

Inclusive asymmetry

Skands, Webber, Winter

- ♦ Expectation: PS inclusive asymmetry = fixed-order result
 - ♦ i.e. Pythia/Herwig/Sherpa → no asymmetry
- ♦ But: recoil effects cause migration between regions of positive and negative rapidity
 - ♦ expectation incorrect
 - ♦ care required when correcting back to parton level using shower prediction



Further asymmetry corrections

- ♦ Electroweak corrections to asymmetry now also understood
 - ♦ simple relation between QED and QCD asymmetry:

$$A_{QED}^q = \frac{36}{5} \frac{\alpha}{\alpha_S} Q_q Q_t A_{QCD} \approx 0.1 - 0.2$$

Hollik, Pagani
Kuhn, Rodrigo
Bernreuther, Si

- ♦ weak corrections not easily related but small
- ♦ NLO+NNLL soft gluon resummation effects also small, <3%, but reduce scale uncertainty.
Ahrens et al.
- ♦ Potentially large EW Sudakov logs resummed using effective field theory techniques
$$\left(\frac{\alpha}{\sin^2 \theta_w} \right)^n \log^{2n} \left(\frac{s}{m_W^2} \right)$$

Manohar, Trott
- ♦ 5% effect overall, but bigger at large top pair inv. mass

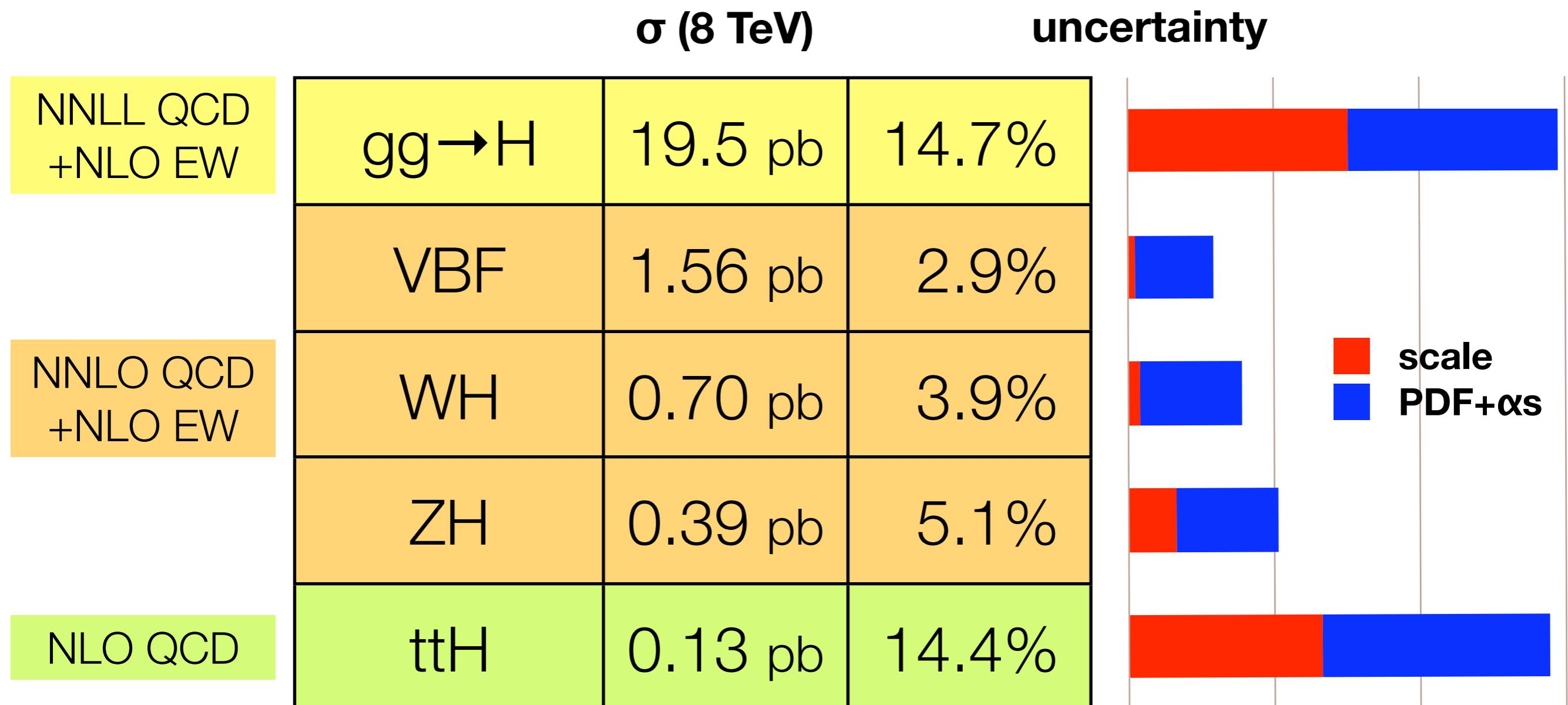
Tevatron results prompted great activity → feed into LHC

Higgs uncertainties

Higgs production at 125 GeV

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>

- ♦ Model testing requires assessment of theoretical uncertainties
 - ♦ uncertainties from **scale variation** and **PDF+strong coupling**



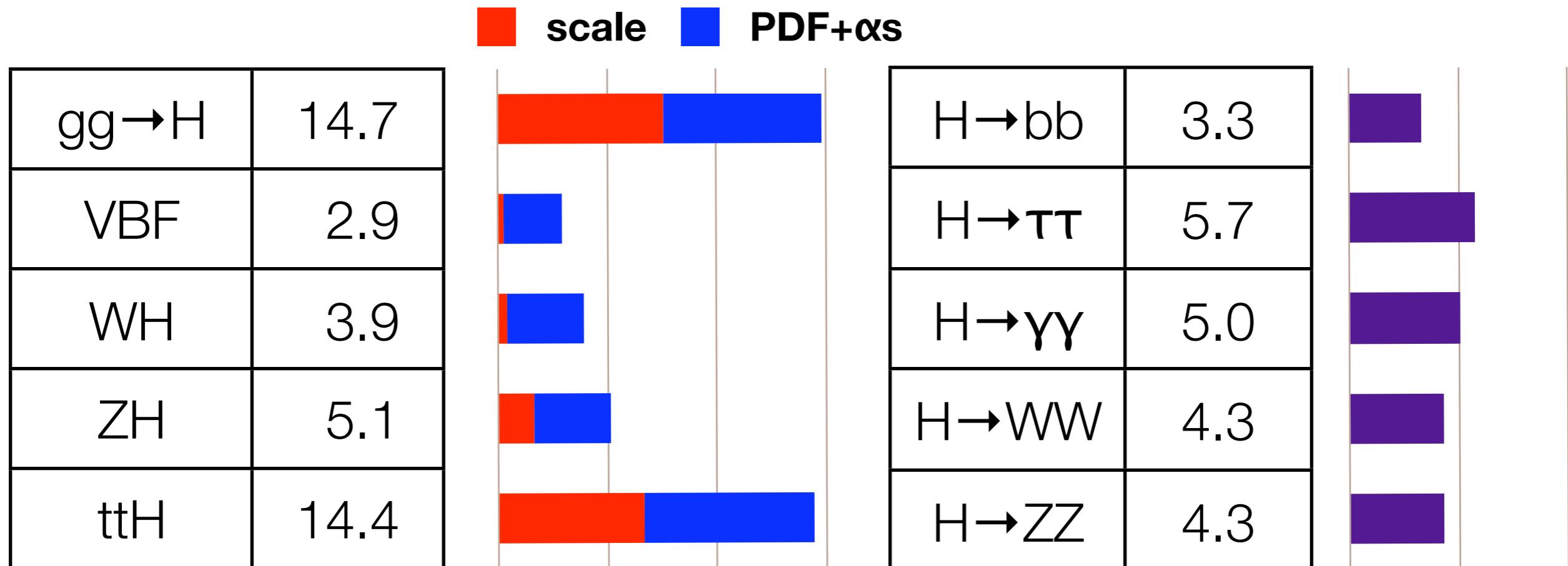
Higgs decay at 125 GeV

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>

- ♦ Uncertainty on branching ratios **combined** from two sources
 - ♦ parametric (α_s ,masses) and higher order theory

	BR	uncertainty	
NNNLO QCD +NLO EW	$H \rightarrow bb$	0.58	3.3%
	$H \rightarrow \tau\tau$	0.063	5.7%
NLO QCD +NLO EW	$H \rightarrow \gamma\gamma$	0.0023	5.0%
	$H \rightarrow WW$	0.22	4.3%
	$H \rightarrow ZZ$	0.026	4.3%

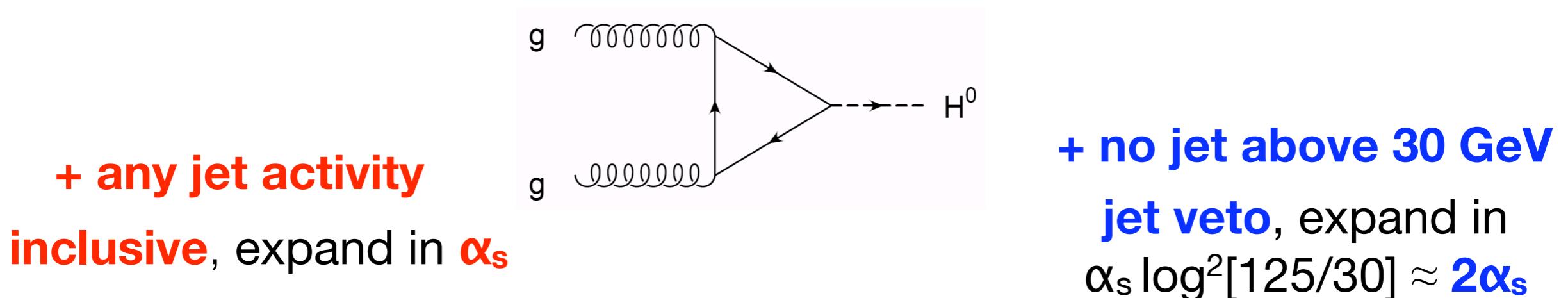
Total SM Higgs uncertainty



- ♦ Conservative estimate of uncertainty in SM predictions
 - ♦ absolute: gg \rightarrow H \rightarrow ZZ/WW/γγ/ττ 20%
 - ♦ relative, e.g. $\frac{\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}}{\text{gg} \rightarrow \text{H} \rightarrow \gamma\gamma}$ 5 - 10%

Inclusive vs. binned

- ♦ Quoted uncertainties only on inclusive cross sections.
- ♦ Analysis requirements often quite different:
 - ♦ lepton cuts mostly harmless
 - ♦ jet vetoes or counting in jet bins can be dangerous
- ♦ Incomplete cancellation of infrared divergence introduces log.



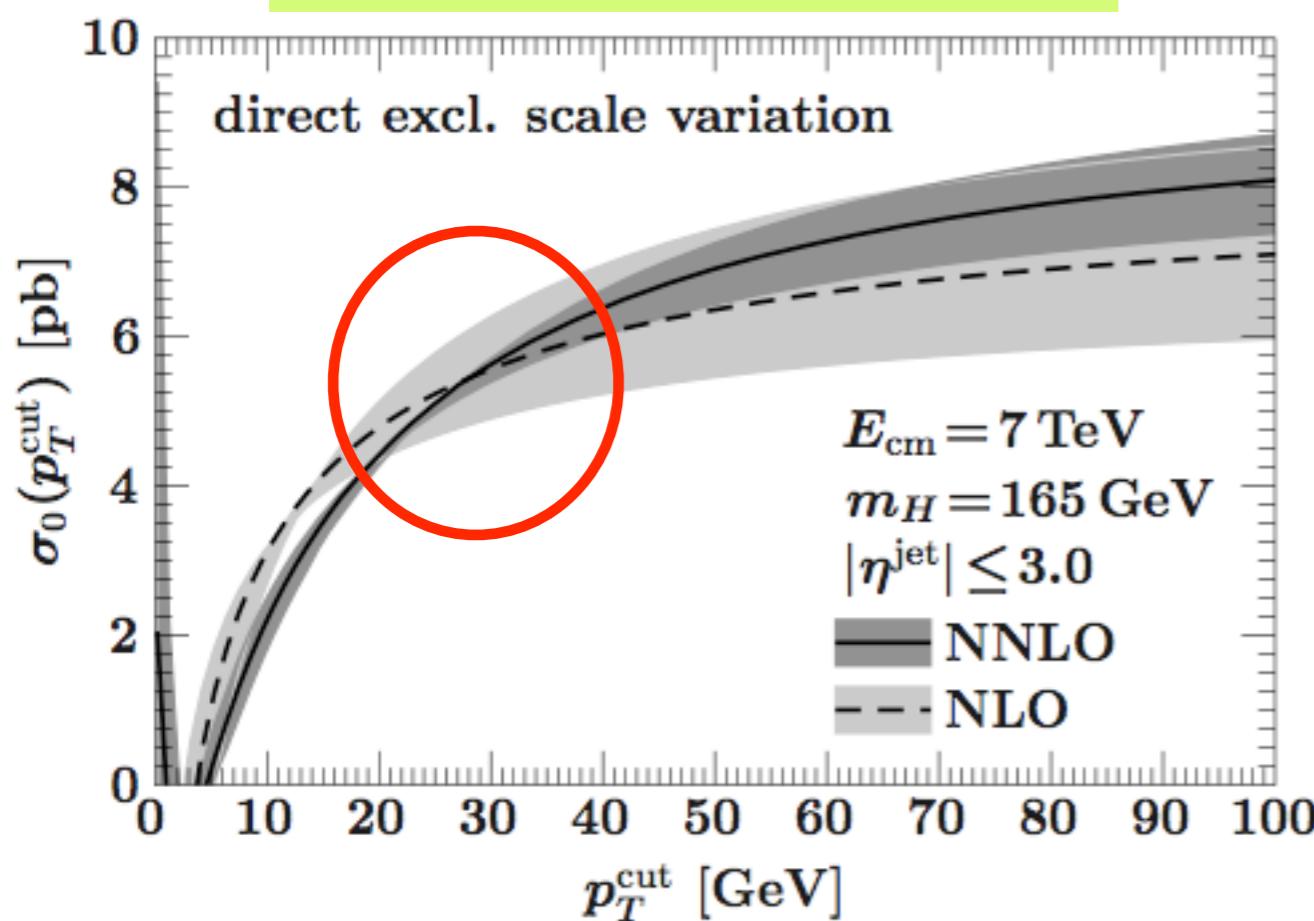
- ♦ Expect worse perturbative behavior → resum large logs

Estimating uncertainty

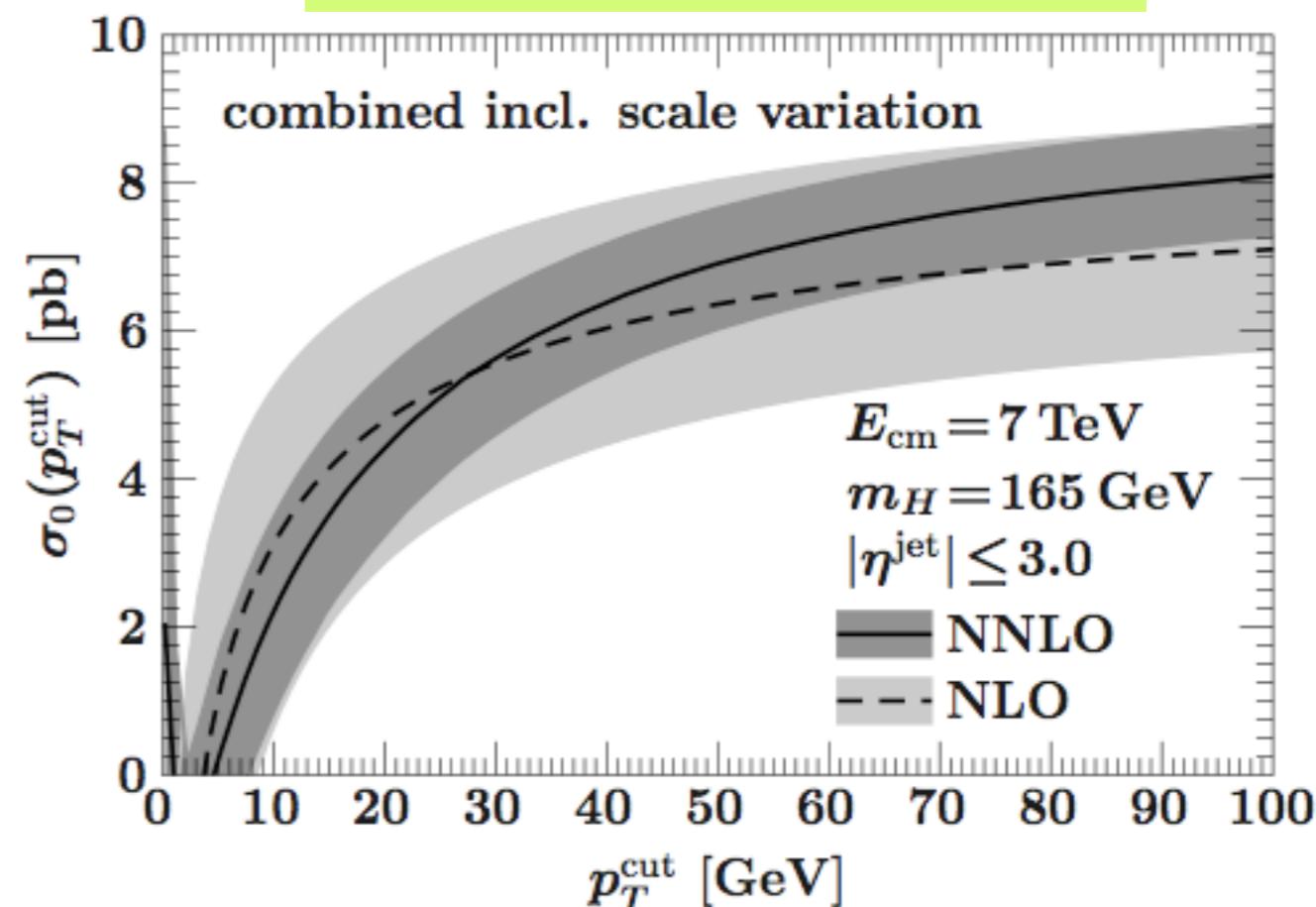
- ♦ Naive scale variation too optimistic.
 - ♦ accidental (numerical) cancellation of terms

Stewart, Tackmann

Naive scale variation



Correlated variation



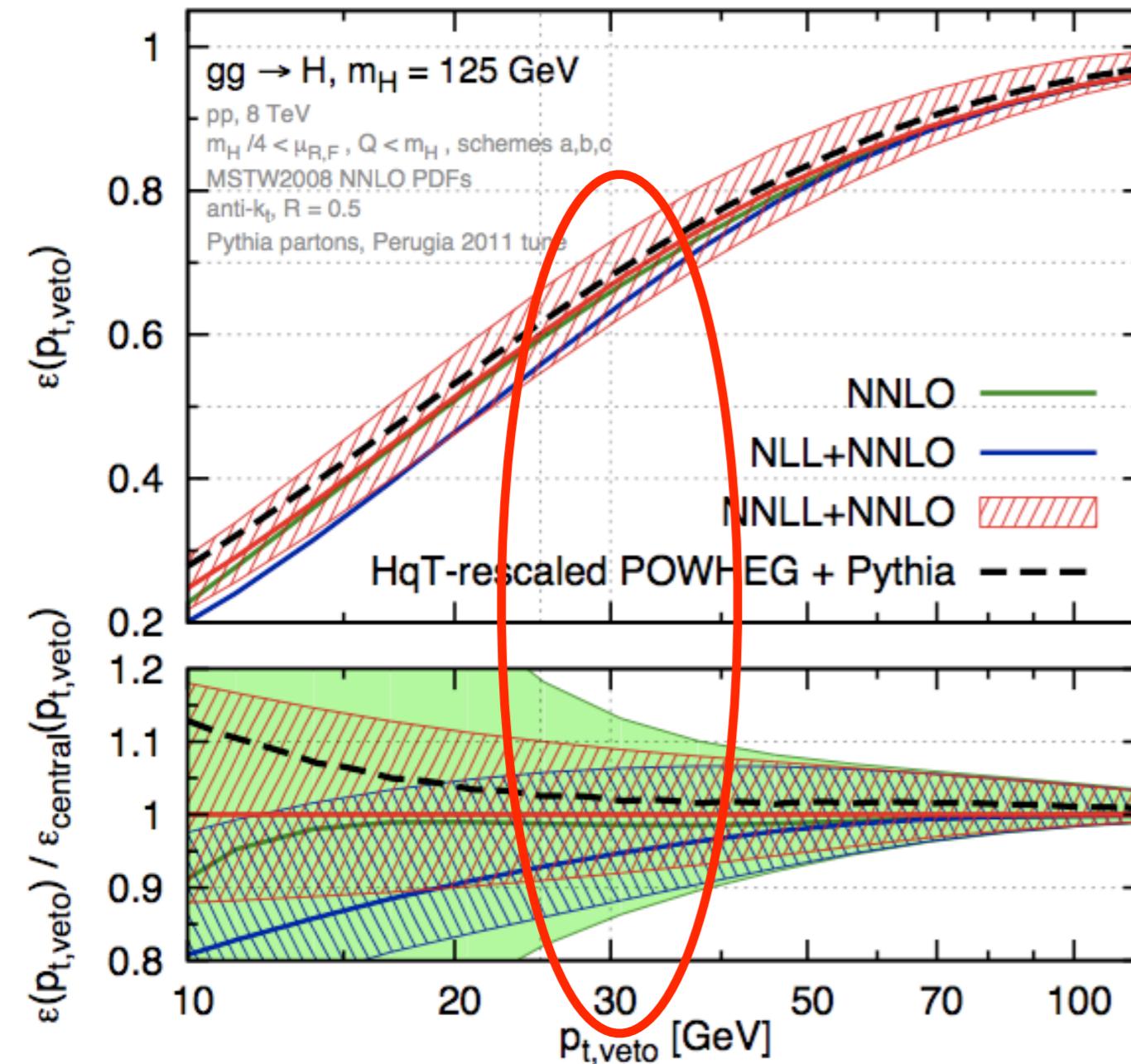
- ♦ Correlated uncertainties look better: typical veto, NNLO $\sim 15\%$.

Resummed predictions

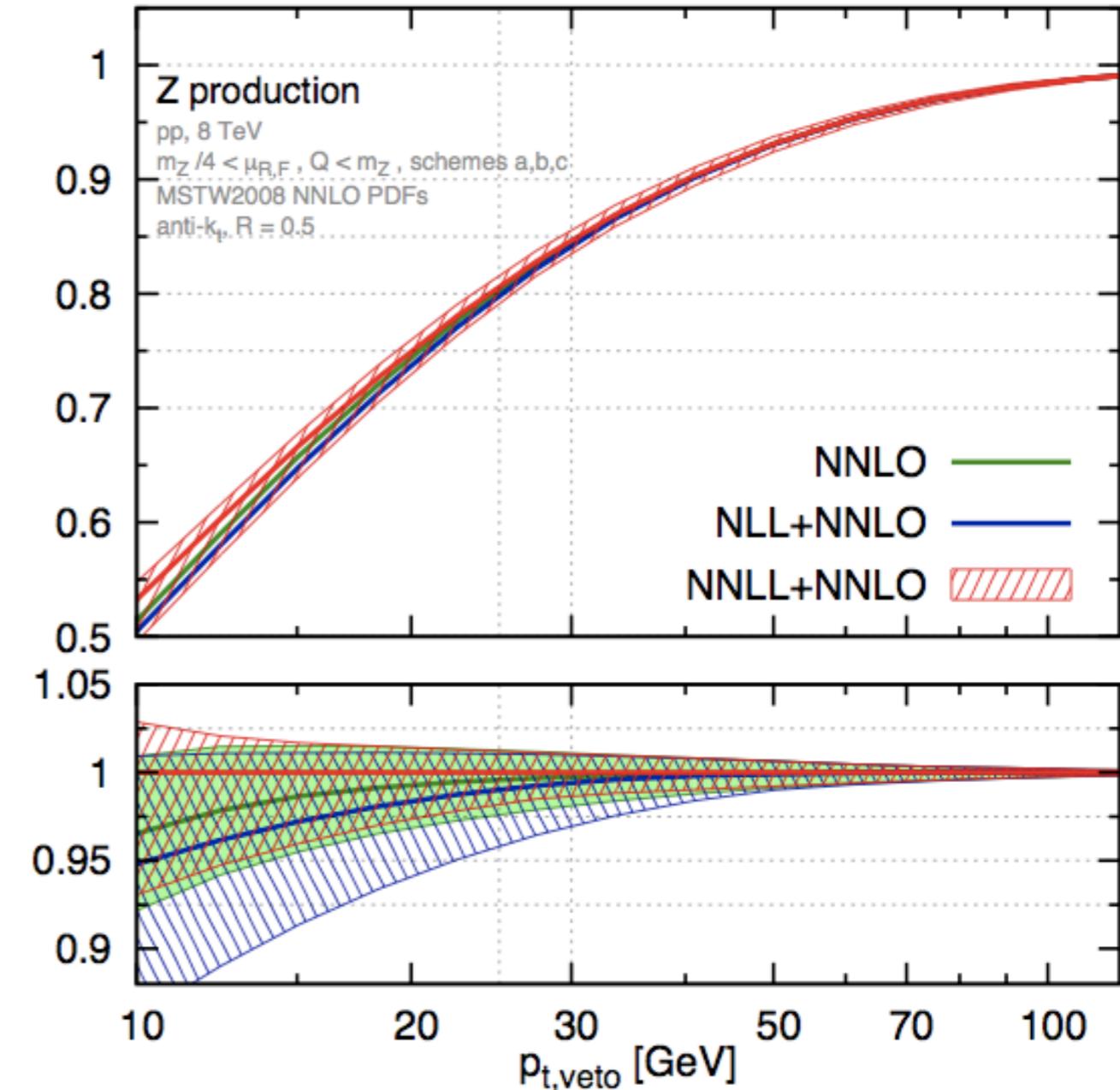
- ♦ Much work on resumming the large logarithms for a better understanding of jet-vetoed cross sections
 - ♦ NLL+NNLO Higgs and Z
(numerical resummation using CAESAR) Banfi, Salam, Zanderighi
 - ♦ NNLL+NNLO Higgs
(SCET - soft-collinear effective theory) Becher, Neubert
 - ♦ NLL and clustering logs
(study of class of logs, $\alpha_s \log[m_H/p_T(\text{veto})] \log[R]$) Tackmann, Walsh, Zuberi
 - ♦ NNLL+NNLO Higgs and Z
(adapt results on boson p_T resummation) Banfi et al
- ♦ Healthy debate on accuracy of different techniques

Jet veto uncertainty

Banfi, Monni, Salam, Zanderighi



NNLL+NNLO Higgs uncertainty:
~10% for typical vetoes

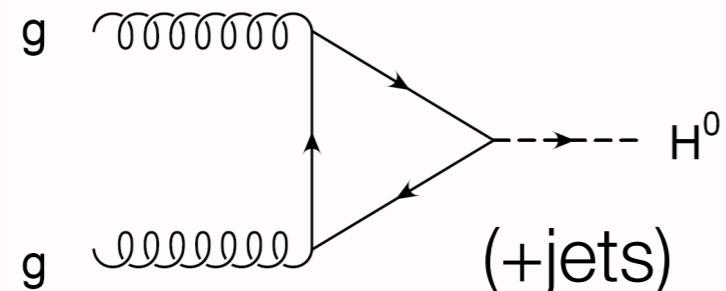


NNLL+NNLO Z uncertainty:
~2% (less radiation)

0-jet cross section uncertainty

- ♦ Most Higgs sensitivity from the 0-jet bin in gluon fusion
- ♦ Example for $m_H=125$ GeV

approx. uncertainty

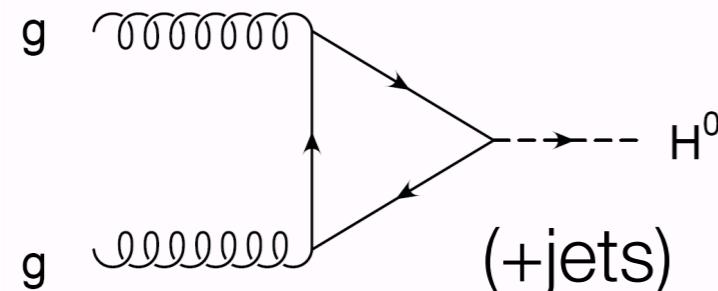


15% (scale~7%, pdf+ α_s ~8%)

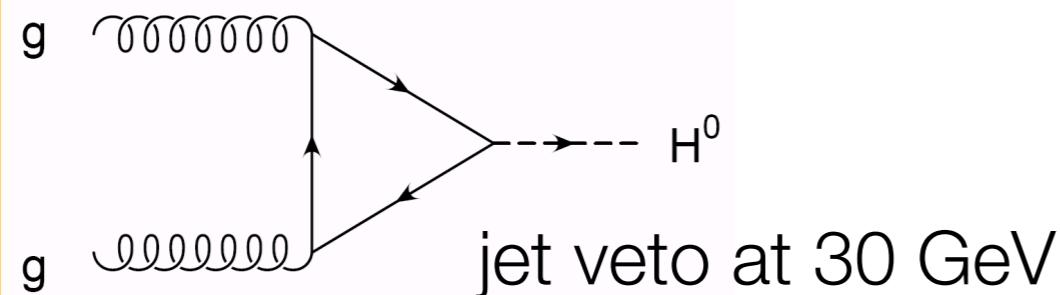
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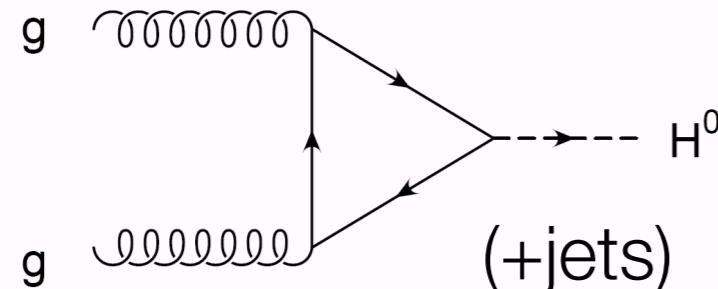
20% (scale→11% from jet veto)

Banfi et al

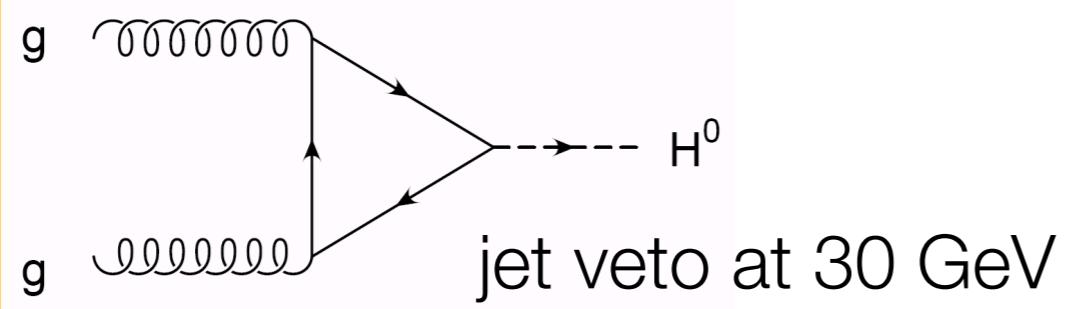
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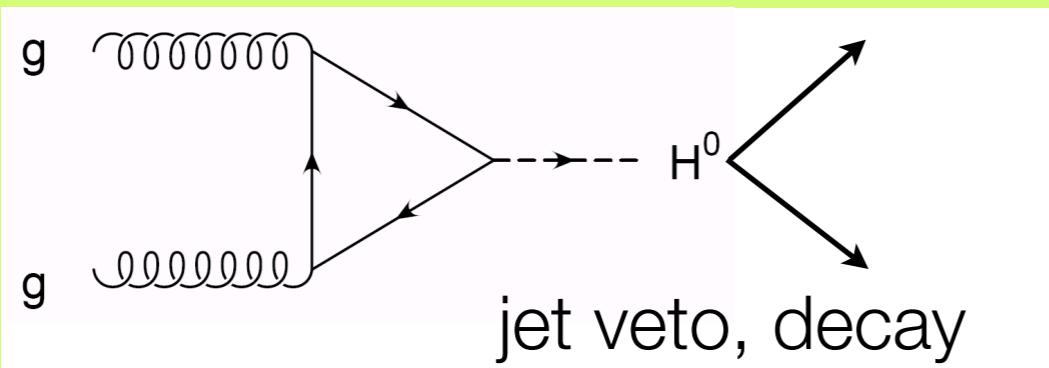
approx. uncertainty



15% (scale~7%, pdf+ α_s ~8%)



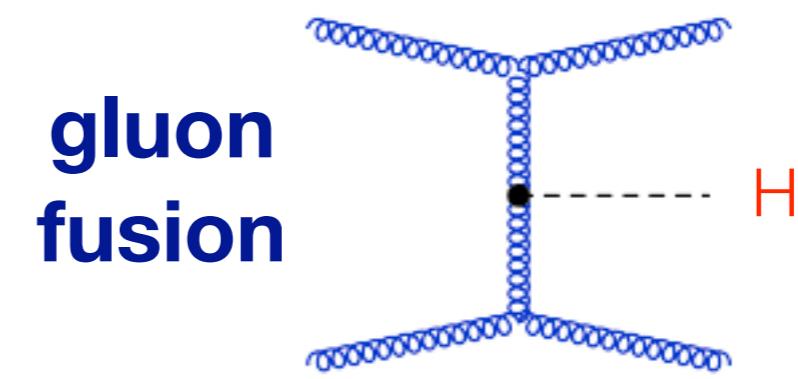
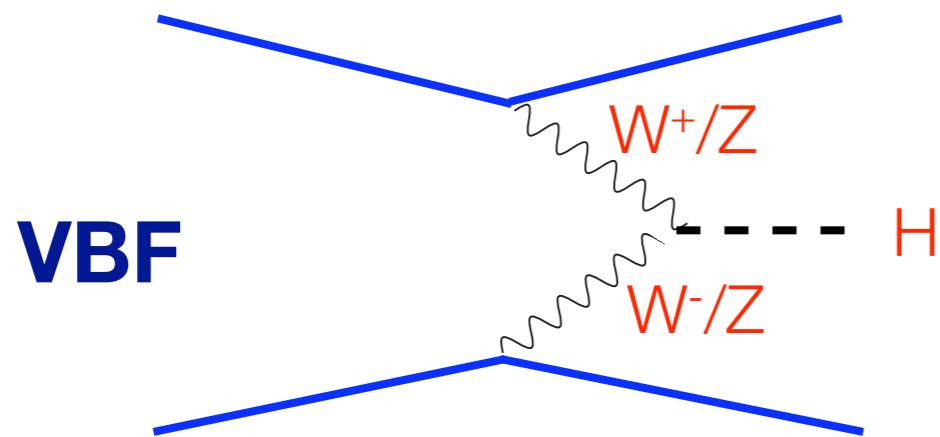
20% (scale→11% from jet veto)
Banfi et al



25% (BR uncertainty ~ 5%)

Higgs search: 2-jet bin

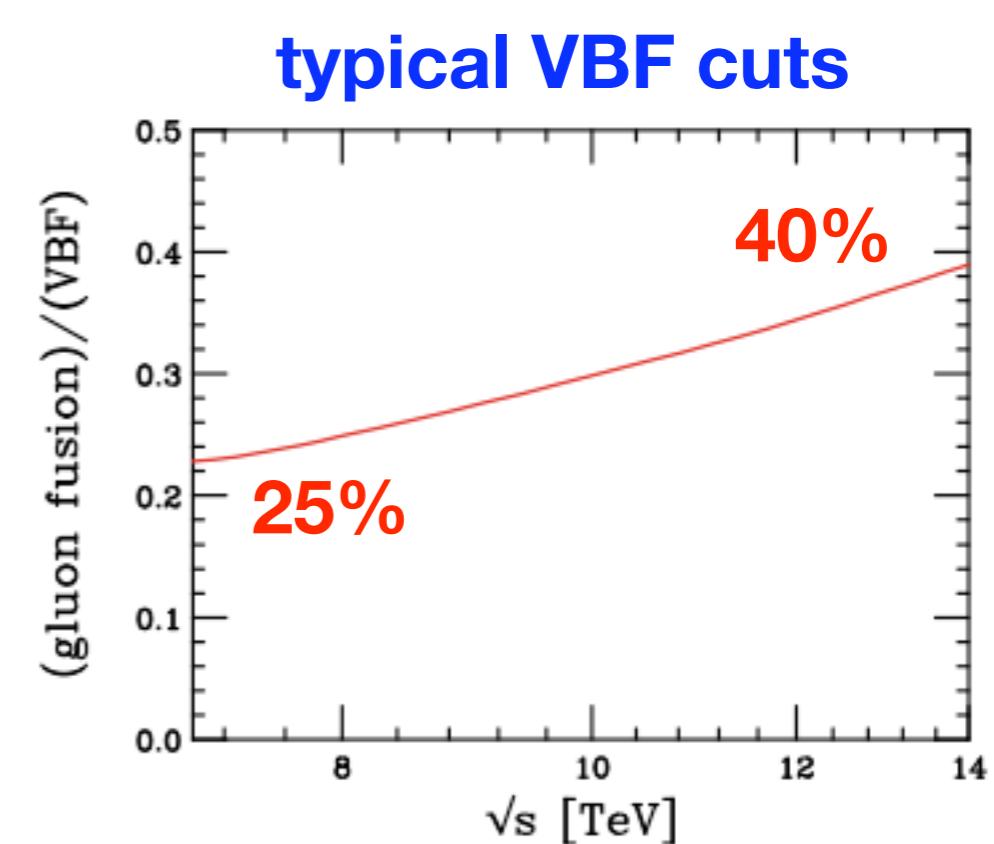
- ♦ Higgs sensitivity enhanced by VBF channels, special cuts to select events with 2 jets at large rapidity separation



- ♦ Extra sensitivity + prospects for test of production/decay mechanism (accuracy $\sim 3\%$)
- ♦ Contamination from gluon fusion (accuracy $\sim 25\%$)

Berger, JC, Ellis, Williams, Zanderighi

gg \rightarrow H + 2 jets dominates
uncertainty 6% : 2%



Concluding remarks

- ♦ Perturbative QCD continues to play an important role
- ♦ Identifying characteristics of the newly-discovered particle requires an accurate modelling of both signals and backgrounds
 - ♦ if it's a Higgs boson, lots of sharpened pQCD tools at the ready
- ♦ Unprecedented access to ...
 - ♦ NNLO accuracy - both for pdfs and matrix elements
 - ♦ NLO+PS predictions for direct comparison with data
 - ♦ NLO for complex final states
- ♦ More to come
 - ♦ matching NLO+PS
 - ♦ NNLO: on the horizon $gg \rightarrow tt$, charge asymmetry